

A History of Rotorcraft Comprehensive Analyses

Wayne Johnson
wayne.johnson@nasa.gov
NASA Ames Research Center
Moffett Field, California, USA

ABSTRACT

A history of the development of rotorcraft comprehensive analyses is presented. Comprehensive analyses are digital computer programs that calculate the aeromechanical behavior of the rotor and aircraft, bringing together the most advanced models of the geometry, structure, dynamics, and aerodynamics available in rotary wing technology. The development of the major codes of the last five decades from industry, government, and universities is described. A number of common themes observed in this history are discussed.

INTRODUCTION

The digital computer programs that calculate the aeromechanical behavior of rotorcraft are called comprehensive analyses. Comprehensive analyses should bring together the most advanced models of the geometry, structure, dynamics, and aerodynamics available in rotary wing technology, subject to the requirements for accuracy and the constraints of economy. These computer programs calculate rotorcraft performance and trim, blade motion and airloading, structural loads, vibration, noise, aeroelastic stability, and flight dynamics. The multidisciplinary nature of rotorcraft problems means that similar models are required for all of these jobs. A comprehensive analysis performs these calculations with a consistent, balanced, yet high level of technology. Because the tasks require a similar level of technology and similar models, they are best performed with a single tool. The history of the development of computer programs for rotorcraft started with the alternative approach of developing multiple codes separately for individual disciplines such as performance, dynamics, and handling qualities. Often the range of application of a particular analysis was restricted, perhaps to improve efficiency, but more often for historical reasons. Such experience with early codes provided solid evidence of the resulting inefficient use of development and application resources, and inevitable disparity of treatment of the various problems.

The word “comprehensive” has several different implications in rotorcraft aeromechanics, all encompassed by the ideal analysis. Comprehensive refers to the need for a single tool to perform all computations, for all operating conditions and all rotorcraft configurations, at all stages of the design process. The technology is comprehensive,

covering all disciplines with a high technology level. The models are comprehensive, covering a wide range of problems, a wide range of rotorcraft configurations and rotor types, and dealing with the entire aircraft. The analysis is readily adapted to new configurations and new designs. The software is comprehensive, with the flexibility to adapt or extend the codes to new problems and new models. The software is reliable and accurate yet efficient and economical—characteristics achieved through correlation and verification. The software is built with good programming practices and extensive documentation, ensuring ease of test and maintenance. While the real software falls short of this ideal, helicopter problems are inherently complex and multidisciplinary, so helicopter analyses are always driven toward consideration of these “comprehensive” issues.

Design and development of rotorcraft requires the capability to calculate rotor performance and maneuver loads. To provide such calculations, a comprehensive analysis has a rotor wake model, accounts for drag and stall and compressibility of the rotor aerodynamics, includes nonlinear dynamics and elasticity of the rotor blades and airframe, and models the entire aircraft. The entire aircraft in flight is analyzed, although often the code treats just the rotor. Calculating vibration, aeroelastic stability, and flight dynamics within the comprehensive analysis is best, but may be accomplished with separate codes. The aeromechanics of a rotor alone in a steady operating condition are certainly complicated, yet it is important to analyze multiple rotors and maneuvers.

HISTORY

Comprehensive analyses have their origins in the programs developed as soon as digital computers first became available to engineers in the 1960s. Figure 1 identifies some major comprehensive analyses, and shows the developer and the approximate time the code was introduced.

Presented at the AHS 69th Annual Forum, Phoenix, Arizona, May 21–23, 2013. This is a work of the U.S. Government and is not subject to copyright protection in the United States.

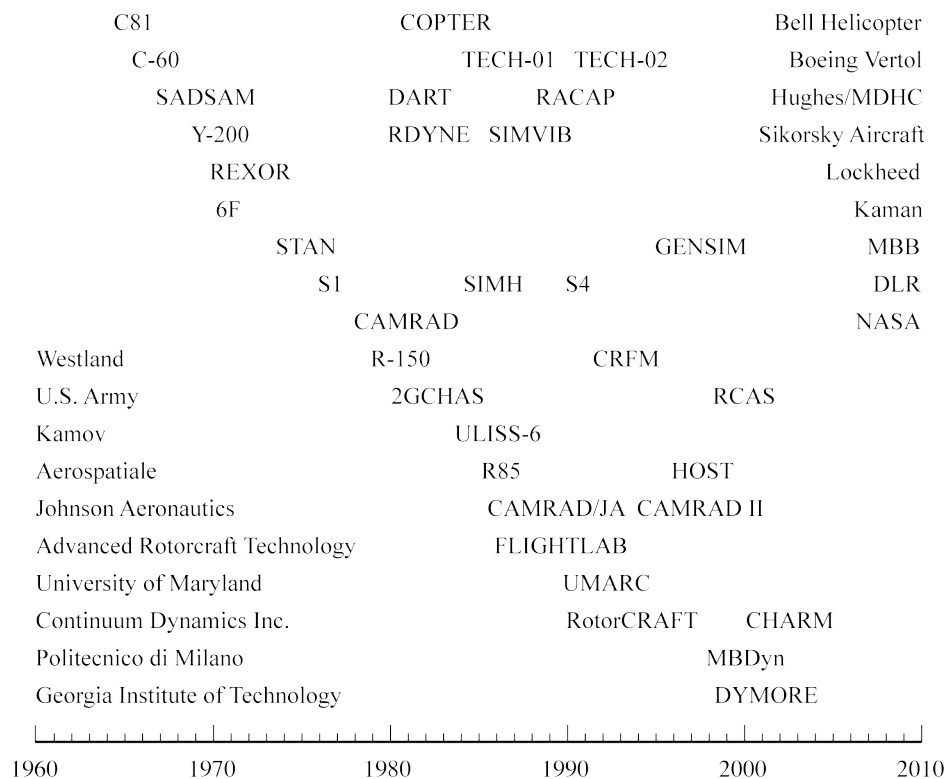


Figure 1. Comprehensive analyses.

THE BEGINNINGS

The prototype of rotorcraft comprehensive analyses is the helicopter flight simulation program C81, which was developed by Bell Helicopter with major support from the U.S. Army (Figure 2). The objectives as stated by Bennett (1973) were quite modern: "The development has followed certain guidelines. First, the analysis must describe a wide variety of helicopter configurations—single rotor, compound, tandem, or side-by-side; it must also cover a broad range of flight conditions—hover, transition, cruise, or high speed. The analysis must have a uniform texture; i.e., the level of complexity of the different phases (aerodynamic, dynamic, and rotor analysis) must be uniform. The program must be applicable to diverse types of analysis—performance, stability and control, or rotor loads. The program must be user oriented in terms of preparing the input data and interpreting the results. And finally, the output format must facilitate comparison with flight and tunnel test data."

The early development of C81 was described by Corrigan, Bennett, and Hsieh (2001). The origin of C81 was attributed to Blankenship and Harvey (1962), and Duhon, Harvey, and Blankenship (1965). The prerequisite was the modern digital computer, first available at Bell Helicopter in 1959. These early papers describe the new experience of developing a computer program for engineering applications. Blankenship and Harvey (1962) devoted a

paragraph to justifying the choice of a digital computer instead of an analog computer. The model was restricted to level flight and single-main-rotor configurations. Key aspects of this first code were that it modeled the entire aircraft (not just the rotor) and covered both aerodynamics and structural dynamics, earning the description "comprehensive." Duhon, Harvey, and Blankenship (1965) described a computer program for the analysis of maneuver performance and handling qualities, incorporating rotor aerodynamic modeling and blade load calculation as in Blankenship and Harvey (1962). The program was extended and used to investigate rotorcraft gust response in 1965–1967 (Harvey, Blankenship, and Drees, 1969). During this work, the first complete documentation of the software was prepared (Blankenship and Bird, 1967). The code was applicable to single-rotor, tandem, side-by-side, and compound configurations, with articulated, semi-rigid, and rigid rotors; and calculated trim and maneuvers, subject to gusts. A harmonic balance method was used to solve for the blade flap motion. Livingston, Bird, and McLarty (1970) added the capability to model stop-fold rotor concepts, using time integration with rigid blades.

By 1967 (Blankenship and Bird, 1967), the code was called "Rotorcraft Flight Simulation Program" and designated C81. The Eustis Directorate of the U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL) sponsored Bell Helicopter in a series of

major upgrades and extensions to C81. Bennett and Blankenship (1972; apparently never actually published) introduced time integration for elastic blade motion based on a modal representation. Davis, Bennett, and Blankenship (1974) improved the airframe and blade aerodynamic models (in particular by adding the capability to use airfoil tables, with a format developed by E. E. Austin of Eustis), investigated numerical integration methods, and expanded the documentation. U.S. Army support of C81 development continued into 1980 with McLarty, Van Gaasbeek, and Hsieh (1977); Van Gaasbeek, McLarty, Sadler, and Hsieh (1979); and Van Gaasbeek and Hsieh (1981), which documented the last official version released to the public. C81 development continued at Bell Helicopter with the final C81 version in 1984.

The U.S. Army adopted C81 for rotorcraft simulation by 1973 (Austin and Vann, 1973; Vann, Mirick, and Austin, 1973). The software was provided by Bell Helicopter to qualified users for design and analysis of rotary wing aircraft. Proposals submitted for major aircraft development programs were required to include C81 input decks, beginning with the Utility Tactical Transport Aircraft System (UTTAS) competition in 1972 and continuing through Light Helicopter Experimental (LXH) in 1988. Several major efforts to correlate C81 calculations with test data were sponsored by the U.S. Army in the 1970s. The work covered AH-1G flight test, OLS flight test, and H-34 model data by Bell Helicopter (Van Gaasbeek, 1975, 1980; Freeman and Bennett, 1974), Bo-105 flight test data by Boeing (Staley, 1976), and H-53 and S-67 flight test data by Sikorsky Aircraft (Briczinski, 1976). The results ranged from inconclusive to disappointing to poor. The industry position against universal adoption of C81 was clear. Moreover, the C81 program had grown difficult and unwieldy to upgrade and maintain, and upgrades were not always successful (Corrigan, Bennett, and Hsieh, 2001). Development of comprehensive analyses at Bell Helicopter continued with COPTER, as described below.

REXOR (Revised and Extended Rotor) was developed by Lockheed (Figure 3). In the mid-1960s, J. A. Hoffman implemented an analog/hybrid program called Rotor Analysis, for practical real-time stability and flight control analysis, and a digital, non-real-time version originally developed to check the analog simulations. Rotor Senior was an expanded, more detailed extension of this digital analysis. During flight tests of the AH-56A, problems with rotor stability were encountered that required the support of Rotor Senior, as a fully nonlinear model, in addition to linear analysis methods. Rotor Senior updated became REXOR. Motivated by AH-56A development, the code started as a model of the entire aircraft. The code was an interdisciplinary analysis for predicting the flight envelope in terms of performance, dynamic stability, handling qualities, and transient loads (Kerr, Potthast, and Anderson, 1972). The model consisted of a rigid airframe, rotor pylon and rotor speed motion, a control gyro, and blade modes (but quasi-static torsion motion), with a uniform plus linear

inflow variation over the disk. Time integration was used for the trim and transient tasks, and the equations were perturbed for a linear system analysis. The analysis grew out of the requirement for a nonlinear handling qualities evaluation tool, and was mechanized in a fashion that provided a capability to predict rotor loads affected by rotor-airframe interaction in steady-state and transient flight conditions (Carlson and Kerr, 1973). This mechanization was accomplished by a loads specialist modifying the nonlinear handling qualities model for rotor loads calculations. Other specialists developed their own modifications, leading to a state with inconsistent versions, unwieldy data management, and a requirement to completely restructure the code. Recognizing the problems with this code development approach, a new approach was developed based on combining the capabilities of a team of analysts from several specialties to create a versatile model (Carlson and Kerr, 1973). This new approach, based on an analyst team with an overall system manager, dealt with model derivation, code structure, data management, checkout, and documentation to produce REXOR.

C-60 (Aeroelastic Rotor Analysis Program) was developed by Boeing Vertol to calculate rotor structural loads in steady-state flight conditions (Gabel, 1973; Figure 4). The wake model included tip and root vortices, with rigid geometry. Articulated and hingeless blades were modeled with coupled flap-torsion and uncoupled lag deflections. A Fourier series representation was used for the trim solution. The origins of C-60 are traced to a 1961 code with linear aerodynamics and uniform inflow. Nonlinear aerodynamics and non-uniform inflow were added in 1965, airfoil tables in 1967, and a consistent solution for wake strength, downwash, and airloads in 1968. A nonlinear unsteady aerodynamic model was developed to improve the calculation of performance and control loads (Harris, Tarzanin, and Fisher, 1970; Tarzanin, 1972). Development of comprehensive analyses at Boeing continued with TECH-01 and TECH-02, as described below.

Y-200 (Normal Modes Aeroelastic Analysis) was developed by Sikorsky Aircraft (Arcidiacono and Carlson, 1973; Figure 5). The flap-lag-torsion equations of motion for the rotor blade were developed by Arcidiacono (1969) for an investigation of flutter, stall flutter, torsion divergence, and flap and flap-lag stability. The equations were expanded in the uncoupled vibration modes of the blade. The time integration method was based on Tanner (1964). Unsteady aerodynamics, dynamic stall, and variable inflow were added by Arcidiacono, Carta, Casellini, and Elman (1970). Also, the equations of motion were extended to include fuselage motion for maneuver effects on control loads. The induced velocity was calculated by a separate Circulation Program, using a rigid wake geometry model similar to Piziali and DuWaldt (1962). Iteration between the Circulation Program and the Blade Response Program was required. Bergquist (1973) analyzed a single rotor or compound helicopter, including rotor and airframe response in free flight, to assess helicopter gust response. By 1973,

the Blade Response Program, Circulation Solution Program, and Wake Geometry Program were linked to obtain the circulation consistent with blade response and wake geometry (Arcidiacono and Carlson, 1973). The wake geometry of Landgrebe (1969) was used and eventually the Rotorcraft Wake Analysis (Landgrebe and Egolf, 1976). Development of comprehensive analyses at Sikorsky Aircraft continued with RDYNE and SIMVIB, as described below.

SADSAM (Structural Analysis by Digital Simulation of Analog Methods) was a finite-element structural analysis developed by MacNeal-Schwendler Corporation in 1963; Figure 6. The helicopter version SADSAM IV was developed for Hughes Tool Company (Simpson, 1967). As described by Neff (1974) and Ormiston (1974), SADSAM used a time-domain solution procedure with linear or nonlinear section aerodynamics and uniform inflow. When MacNeal-Schwendler Corporation stopped supporting SADSAM in the late 1970s, development continued at Hughes and later McDonnell Douglas Helicopter Corporation, with the code renamed DART (Dynamics Analysis Research Tool). Extensions included nonlinear steady and unsteady aerodynamics models for the blade, and an autopilot for trim (Callahan and Bassett, 1988). DART had a flexible structural modeling capability, important for aeroelastic stability analysis (Silverthorn, 1982). Its formulation as a digital implementation of analog computing circuits was unique.

Only a decade after digital computers became available to engineers, helicopter companies had mature codes for calculation of flight dynamics and structural loads. An Advisory Group for Aerospace Research and Development (AGARD) meeting held in March 1973 provided a snapshot of rotor modeling state of the art in industry, including papers from Kaman, Boeing, Aérospatiale, Sikorsky, Bell, Westland, Messerschmitt-Bölkow-Blohm (MBB), and Lockheed.

At an American Helicopter Society meeting in February 1974, a comparison of blade and hub loads calculations for a hypothetical helicopter rotor was presented (Ormiston, 1974). The comparison covered analyses from NASA, Bell, Boeing, Hughes, Kaman, Lockheed, Massachusetts Institute of Technology (MIT), Office National d'Études et de Recherches Aéropatiales (ONERA), Sikorsky, and United Aircraft Research Laboratory (UARL). The more capable codes were called "multi-use, global programs." Significant differences were observed in the loads calculated by these codes, attributed to all parts of the problem: numerical solution methods, structural dynamics, and aerodynamics. To some extent the differences were also due to differences in the tasks that the codes could handle. Asked whether the government should work toward a single-rotor loads analysis following the general precedents set by NASTRAN (NASA Stress Analysis Program), the participants expressed a desire for such a program but skepticism that it would be practical or even possible, and concern whether any program could be

general enough to anticipate all future configurations (Ormiston, 1974). Notably R. H. MacNeal (a principal developer of NASTRAN) opposed supporting a single analysis, based on the value of diverse analyses when the physics of the problems and the methods of analysis were still uncertain.

CAMRAD

CAMRAD (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics) was developed at Ames Research Center for NASA and the U.S. Army (Johnson, 1980, 1981; Figure 7). The objective was to produce an analysis that used recently developed technology, applicable to a wide range of problems and wide class of vehicles. Most comprehensive analyses available at the time had been developed for only a particular type of helicopter or a particular technical problem. With separate analyses for various problems, it followed that available technology was not uniformly utilized. Previous work on dynamic stall led to a method to solve the rotor blade equations for periodic motion (Johnson, 1969). Work on blade-vortex interaction dealt with wake models, lifting-line theory, and lifting-surface theory (Johnson, 1970). Stability investigations during 1974–1976 produced linearized equations of motion for the rotor and aircraft (Johnson, 1977). These stability investigations focused on tiltrotor whirl flutter, so consideration was given to high-inflow and large-angle aerodynamics, and coupled rotor and body dynamics. The development of CAMRAD during 1978–1979 was built on these earlier investigations. The dynamics models of the rotor and airframe from the stability analysis were used, but in nonlinear form. The solution procedures were extended to cover trim, inflow, and motion iterations. A new wake analysis was developed to calculate the induced velocity at the rotor blade, incorporating the free-wake geometry of Scully (1975), the only part of the code obtained from an outside source. The new wake model was a major justification for the development of CAMRAD, reflected in initial applications of the code. CAMRAD was also intended to provide a solid basis for further development of rotary wing analysis. CAMRAD modeled a general two-rotor aircraft, or a rotor in a wind tunnel; and articulated, hingeless, gimbaled, or teetering rotors with an arbitrary number of identical blades. The model included elastic blades, an elastic airframe, and a drive train. A single load path was assumed for the blade structure. The trim task solved for the periodic motion (by harmonic method) in a steady-state flight condition. The flutter task analyzed linearized equations (analytically derived). A flight dynamics analysis used rotor stability derivatives, and the maneuver analysis was obtained with a quasi-static rotor response solution.

CAMRAD/JA was developed by Johnson Aeronautics during 1986–1988 (Johnson, 1988). Applications of CAMRAD led to the implementation of a number of separate extensions and modifications. CAMRAD/JA was an extensively revised software implementation, incorporating

new capabilities, written using a software tool that facilitated modifications. The wake model was extended to cover dual-peak blade circulation distributions, second-order lifting-line theory, and rollup representations. The aerodynamic model was extended to cover swept tips and wing/body interaction in terms of velocities at the rotor disk. Loose coupling with computational fluid dynamics (CFD) codes was implemented in terms of prescribed airload increments and partial angle-of-attack calculations for boundary conditions. A self-tuning regulator for higher harmonic control simulation was added. The structural dynamic model was not changed. A version of the CAMRAD/JA wake model developed for NASA (Johnson, 1988), still using the Scully free-wake geometry, was adopted in other comprehensive analyses including COPTER, UMARC, and 2GCHAS.

FIRST GENERATION ANALYSES

These and similar codes of the 1970s are considered the first generation of helicopter comprehensive analyses. Upon review, these powerful and useful tools exhibited a number of common limitations. Generally the codes were developed and verified for only a particular type of helicopter or a particular technical problem, which reflected the specific interest of the originating organization. Correlation and verification were restricted to a limited range of helicopter types or problems. Modeling a new rotor or a new helicopter configuration required new development of dynamic equations. Some codes were continuously upgraded, but without good control of the process, resulting in poor software. Often there was no sound mathematical development of solution procedures. Few codes could perform the full range of required analyses. Much of the available technology was not well or uniformly utilized, notably inflow, wake, wake geometry, and beam models. Structural dynamic models, aerodynamic models, and solution procedures were mixed in the software so that no single model could be changed without considering the entire code, and growth became increasingly harder as each new feature was added.

There was a consensus that such limitations were no longer acceptable, demonstrated by the development of major new codes beginning in the late 1970s and early 1980s. Experience sponsoring and managing rotorcraft code development showed that new approaches were needed and were possible. The emphasis was on flexibility and versatility, through theory using assembly of primitive substructures, modular and structured software architecture, and modern software development methodology. The capability to analyze an arbitrary configuration required that the system be defined and changed by input, without needing new code as long as the required physics were available. Code modifiability was enhanced by good architecture, separating the structural and aerodynamic models and the solution procedures into separate building blocks to be assembled on-demand to deal with a particular aircraft and a particular problem. A building-block approach led to more general, more rigorous models, as each

component must be capable of general analysis. Timely solutions in an engineering environment were essential. Transportability and modifiability were required of the software, with extensive documentation.

Analysis and design of modern rotorcraft requires a tool capable of handling complex configurations with unusual load paths and interactions, and with many subsystems; structural, aerodynamic, and kinematic nonlinearities; arbitrary large motion, including rigid body motions and rotation of components relative to each other; and components that are not defined by the equations and interfaces of structural dynamics. These requirements are best served by a structural dynamic model based on a combination of multibody dynamics and finite elements, coupled in a general fashion with advanced models for the aerodynamics and wakes of wings and bodies.

2GCHAS

2GCHAS (Second Generation Comprehensive Helicopter Analysis System) was developed under the sponsorship of the U.S. Army (Kerr and Davis, 1979; Kerr and Stephens, 1982; Figure 8). By the mid-1970s, the U.S. Army recognized that effective comprehensive analysis capability was an essential part of rotorcraft research and development, and that existing codes were not sufficient. The deficiencies included a lack of flexible modeling capability, an inconsistent level of detail and validity in the mathematical models, difficulties with use, poor software structure and ad hoc architecture, and poor documentation. Experience with the evaluation and development of the Utility Tactical Transport Aircraft System (UTTAS) and Advanced Attack Helicopter (AAH) aircraft supported this assessment (Crawford, 1990). The 2GCHAS project was undertaken to provide the required capability, with requirements derived from consideration of the deficiencies of existing analysis, and the gains possible from new developments in rotorcraft analysis and software engineering. The objective was to produce a comprehensive, interdisciplinary rotorcraft analysis to support design and engineering throughout the life cycle, and to provide a high-quality foundation for research, with rigorous mathematical basis and configuration flexibility in a user-friendly environment, built using modern software design methodology.

In 1976 the decision was made to proceed with development of a new code, following a Government/Industry Working Group that determined the requirements for the next generation of comprehensive analyses. The term "Second Generation" came from a December 1974 proposal by H. I. MacDonald of the U.S. Army. In 1977–1978, the requirements and the software architecture and development approach were investigated in three pre-design studies sponsored by the Aviation Applied Technology Directorate of the U.S. Army: Computer Sciences Corporation (1978) with Bell Helicopter, Control Data Corporation (1978) with Kaman Aerospace

Corporation, and Science Applications Inc. (Hamrick, Copland, Tarzanin, Staley, Hunt, and Burns, 1978) with Boeing Vertol Company. The system architecture would consist of an executive complex and a technology complex. The executive complex was required for an economical, user-oriented, flexible system; to implement a user language; and to handle the databases. The technology complex would be composed of mathematical models of physical subsystems. From the pre-design studies, it was concluded that the technology task was too large for one organization, that the executive development should precede the technology development, and that modern software design methodology should be used. A project office was formed at the U.S. Army Aeroflightdynamics Directorate to direct the development of the system. The project office was responsible for the top-level design of the technology complex, with detailed design and implementation to be done by a number of organizations. Building on the approach described by Kerr, Potthast, and Anderson (1972), it was essential that the system be developed by a team, not by a single analyst, integrating the work of engineers from many research and manufacturing organizations. Each element of the system would be developed by the appropriate specialists, with the team ensuring full integration of the elements. Besides drawing upon expertise throughout the helicopter community, this widespread involvement would promote confidence in the product. A state-of-the-art software development process was used, including structured software and product assurance methodologies.

2GCHAS was developed by a team of five manufacturing companies, three software and small business companies, and three universities. Initial development was described by Stephens, Rutkowski, Ormiston, and Tan (1989). In 1980 the executive complex contract was awarded to Computer Sciences Corporation (CSC). Because of management and resource problems, the effective start of the project was late 1983. The first release of the executive complex occurred in mid-1987, and the contract was concluded in late 1988, followed by a maintenance contract. Early in 1986, four contracts were awarded for components of the technology complex: to Kaman for the solution procedures, to Boeing and United Technologies Research Center (UTRC) for the aerodynamics, to McDonnell Douglas and Sterling Software for the element library, and to Advanced Rotorcraft Technology (ART) for the linear system analysis. In 1987 the remaining two technology contracts were awarded: to Sterling Software and McDonnell Douglas for the input, and to Sikorsky and ART for the output.

There were problems starting the technology complex development. The system design and its mathematical basis were not sufficiently developed; interfaces between the six contracts were not well defined; the contractors were too dispersed geographically to work well as team or communicate effectively; and some contractors were not familiar with the software development methodology and

did not have automated tools (see also Sangha and Straub, 1991). A System Design Team, formed to develop an expanded system design, recommended the development of a prototype and identification of a system integration contractor. The technology contracts were extended to 1990 so that the theory could be adequately developed first, before coding began. A prototype was constructed to address the design concepts and interface definition. In January 1989 a system integration contract was awarded to CSC and ART. The experience showed the importance of working on the theory first, then the software; using common software development tools; and the development of a prototype. A very important lesson learned was that a rigid schedule with flexible requirements was better than a flexible schedule with rigid requirements. The conclusion of 2GCHAS development was described by Rutkowski, Ruzicka, Tan, Ormiston, and Stephens (1991) and Ormiston, Rutkowski, Ruzicka, Saberi, and Jung (1994). Subsequent to the prototype development, the tasks and schedule were revised a final time. The first build of the integrated technology complex with the executive occurred at the end of 1989. The first public release of 2GCHAS occurred in December 1990. A system maintenance contract was awarded to CSC. A system enhancement contract was awarded in 1990 to ART and Sikorsky, with the tasks of improving run-time efficiency, adding technology (better solution procedures, free-wake geometry, CFD interfaces), and conducting validation. Release 2.0 occurred in December 1991 and release 2.4 in August 1995. With the basic development complete, the project office was no longer required, and in December 1998 a principal investigator was appointed (Lim, Panda, Sopher, Cassarino, and Lee, 2000). With release 3.0 in March 2001, the development of 2GCHAS ended. The development effort shifted to RCAS, as described below.

SECOND GENERATION ANALYSES

FLIGHTLAB was developed as a real-time blade-element helicopter simulation by Advanced Rotorcraft Technology, Inc. (Du Val, 1989, 1998, 2001; Figure 8). In work to support the RSRA X-Wing development, ART evaluated the interaction of higher harmonic control with a stability augmentation system, using a combination of the Lockheed REXOR aeroelastic rotor simulation, the vortex wake model of Sadler (1971), and a free-flight model based on the Sikorsky GENHEL flight simulation code. Beginning in 1985, ART restructured the GENHEL blade-element model in use at NASA (Howlett, 1981) to demonstrate the potential for real-time simulation using parallel processing on affordable computers. Based on this experience, ART began in 1986 to develop a generic, modular, reconfigurable analysis for real-time simulation. The Scope language was developed to provide an interactive environment for modeling. A library of primitive model elements was implemented. FLIGHTLAB was commercially available in 1990, as a rapid prototyping environment for rotorcraft modeling and analysis. In 1990 ART became the prime contractor for 2GCHAS system enhancements. Development of 2GCHAS and FLIGHTLAB proceeded in parallel with

FLIGHTLAB focusing on handling qualities analysis and real-time simulation, and 2GCHAS focusing on comprehensive modeling for structures and loads analysis. In 1995 second-generation comprehensive modeling technology was integrated into FLIGHTLAB, including vortex wake aerodynamics, finite element structural dynamics, and a nonlinear beam model (Saber, Jung, and Anastassiades, 1995; Du Val, 2001).

RCAS (Rotorcraft Comprehensive Analysis System) was developed for the U.S. Army by Advanced Rotorcraft Technology, Inc. (Saber, Khoshlahjeh, Ormiston, and Rutkowski, 2004; Figure 8). In the mid-1990s, fundamental deficiencies in the mathematical basis of 2GCHAS were recognized, particularly limitations on maneuver analysis (unable to handle large rigid motion or large elastic structural deformation) and poor computational efficiency (Rutkowski, Ruzicka, Tan, Ormiston, and Stephens, 1991). Saber, Tang, Ware, and English (2000) describe the effort in 1998–2000 to improve 2GCHAS by reducing run time, increasing functionality, and improving robustness. Based on FLIGHTLAB methods, modifications were made to the element library, to the finite element assembly, and to the solution procedures. For efficiency, modal reduction was introduced and a harmonic balance solution added for trim. The 2GCHAS approach using small element motion relative to a global frame (which precluded large maneuvers) was replaced by the FLIGHTLAB approach using a reference frame internal to each element. Rscope (a modified version of the FLIGHTLAB Scope language) was developed to provide an interactive environment for modeling and analysis. In view of these major changes, the code was renamed RCAS. The first formal release (2.0) occurred in June 2003. RCAS had a hierarchical finite element model for the structure, advanced aerodynamic models, and a sophisticated control system representation. The wake models included dynamic inflow, dynamic wake (Peters and He, 1995), the CAMRAD/JA wake with Scully free-wake geometry, and the free-wake geometry of Bhagwat and Leishman (2003). The trim task was solved in the time domain (integration) or frequency domain (harmonic balance), with a Newton–Raphson or autopilot iteration to achieve equilibrium flight. The flutter task analyzed linearized equations. The transient task analyzed large-motion maneuvers.

COPTER (Comprehensive Program for Theoretical Evaluation of Rotorcraft) was developed by Bell Helicopter (Corrigan, Schillings, Yin, and Hsieh, 1988; Yen, Corrigan, Schillings, and Hsieh, 1994; Corrigan, Bennett, and Hsieh, 2001; Figure 2). In 1979 Bell launched COPTER development to produce the technology needed to support Bell products and to maintain a competitive position in the technical community. Originally planned as a new code, cost and development time were reduced by restructuring C81, with a significant benefit in terms of validation plus a number of immediate enhancements of the capability. COPTER was designed for operational efficiency, user friendliness, coding readability, maintainability,

transportability, modularity, and expandability. The code was divided into an executive complex and a technology complex. The first operational version analyzed the aeroelastic stability of hingeless and bearingless rotors by an eigen-analysis of linear equations. At that point it was observed that the simplest way to add technology modules was to begin with C81, validation was becoming an extensive effort, and C81 was still needed by the engineers. So in 1984 the decision was made to proceed with COPTER development by recoding and integrating elements of C81. The final C81 version was produced in 1984, and COPTER replaced C81 in the mid-1980s with the first release in 1986. COPTER modeled two rotors with an arbitrary hub type and elastic blades (using modes), rigid or elastic (modal) airframe, engine and drive train, and control systems. The dynamic stall model of Leishman and Beddoes (1989) was introduced in 1990. In 1987 the CAMRAD wake model with the Scully free-wake geometry was added, and in 1991 the CAMRAD/JA wake model. Corrigan, Bennett, and Hsieh (2001) extended the model to four rotors, introduced a new input format, and modularized the executive complex after many years of effort focused on the technology complex. The result, COPTER 2000, was an enhanced, restructured, modularized descendant of C81. Corrigan, Meyer, Bothwell, and Brown (2006) produced a real-time implementation of COPTER as a piloted desktop Comprehensive Rotorcraft Simulator. COPTER was coupled to the flight simulation program X-Plane. COPTER and X-Plane were executed on separate computers with data exchange procedures.

RDYNE (Rotorcraft System Dynamics Analysis) was developed by Sikorsky Aircraft beginning in the late 1970s (Sopher and Hallock, 1986; Figure 5). The blade elastic model was a new implementation of the equations of Arcidiacono (1969). Wake influence coefficients were obtained from the Rotorcraft Wake Analysis (Landgrebe and Egolf, 1976), with an internal iteration to obtain the circulation consistent with the section loading. Trim was solved as an optimization problem, using a minimum variance controller. The Coupled Rotor/Airframe Vibration Analysis or Simplified Vibration Analysis (SIMVIB) was developed by Sikorsky by creating a base program to assemble components into the coupled rotor and airframe system (Sopher, Studwell, Cassarino, and Kottapalli, 1983). Separate, external programs were used to calculate fuselage aerodynamics, rotor induced inflow, rotor aeroelastic analysis and trim, and empennage excitation. The base program assembled structural dynamic elements and solved for steady-state (periodic) response, transient response, or eigenvalues. Iteration between the base program and the external induced velocity calculation was necessary to obtain a consistent solution. The development of these new rotor dynamics analyses was based on substructure decomposition, with application of software development methodology, and use of an executive system (Sopher, 1989). RDYNE and SIMVIB used the same code for substructure assembly but with different component libraries and different solution procedures.

TECH-01 (Technology One) was developed by Boeing as a highly structured, modular, interdisciplinary analysis (Shultz, Panda, Tarzanin, Derham, Oh, and Dadone, 1994; Figure 4). C-60 was restructured to meet the need for a program designed for long-term maintenance and modifications (Phelan and Tarzanin, 1984). This restructuring also led to near-term improvements as the code became clear and generalized, and errors were identified. TECH-01 was a restructured combination of the dynamics group program C-60 and the aerodynamics group program B-65. B-65 supplied the downwash calculation and some aerodynamic models with rotor/fuselage interference. C-60 supplied the airloads and structural response, including unsteady aerodynamics and dynamic stall, the elastic blade model, fuselage dynamics, and trim. An early version of the free-wake model later used in CDI's RotorCRAFT code was incorporated. TECH-01 calculated the performance and loads for articulated, hingeless, and bearingless rotors in steady-state flight conditions. TECH-02 had a new structural dynamic model for analysis of advanced rotors.

OTHER COMPREHENSIVE ANALYSES

The history of comprehensive analyses in the United States helicopter industry forms a useful story arc. Similar developments were occurring in the world community. In some cases however, the development and history were not extensively documented. A number of other comprehensive analyses have been described. 6F was developed at Kaman Aerospace Corporation; it modeled servo-flap control as well as conventional swashplate control (Lemnios, 1973; Lemnios and Smith, 1972). RCAP (Rotor/Airframe Comprehensive Aeroelastic Program) was developed at McDonnell Douglas Helicopter Company (Sangha, 1988; Sangha, Weisenburger, and Straub, 1990). ULISS-6 was developed at Kamov, and it modeled coaxial rotors including a vortex wake with prescribed geometry (Burtsev, 1991; Bourtsev, Selemenov, and Vagis, 1999). ARMDAS (Advanced Rotorcraft Multidisciplinary Design and Analysis System) was developed at Nanjing University of Aeronautics and Astronautics, China (Yang, Zhang, and Wang, 1996). MBDyn (MultiBody Dynamics) was a multibody, multidisciplinary code that provided a framework for integrated simulation of complex multi-physics problems; it was developed at Politecnico di Milano, Italy (Ghiringhelli, Masarati, Mantegazza, and Nixon, 1999; Quaranta, Bindolino, Masarati, and Mantegazza, 2004). Helidyn+ was developed at Middle East Technical University, Turkey (Yavrucuk, Tarimci, Katircioglu, Kubali, and Yilmaz, 2010).

UNITED STATE DEVELOPMENTS

UMARC (University of Maryland Advanced Rotorcraft Code) was developed at the University of Maryland (Bir, Chopra, and Nguyen, 1990; Bir and Chopra, 1994; Figure 9). The analysis evolved from the finite element formulation developed by Sivaneri and Chopra (1982, 1984). Graduate students had developed many sophisticated codes for investigation of coupled trim and rotor response, blade and

hub loads, aeroelastic stability, ground and air resonance, vibration, gust response, higher harmonic control, dynamics of composite rotors, optimization, and coupling with CFD. These codes were applied to a wide range of configurations including articulated, hingeless, and bearingless rotors, servo-flap control, and tiltrotor aircraft. The capabilities of these separate codes were integrated into the single comprehensive code UMARC. A finite element model of the blade was used, including nonlinear geometry and composite section, and multiple load paths. The blade element aerodynamics was based on Leishman and Beddoes (1989). The CAMRAD wake model was used. For trim, the periodic blade motion was obtained by a time-finite-element solution. For stability, linear equations were analyzed. UMARC has incorporated the free-wake geometry models of Bagai and Leishman (1995) and Bhagwat and Leishman (2001).

DYMORE was developed beginning in the late 1990s at the Georgia Institute of Technology (Bauchau, Bottasso, Dindar, Murty, Rusak, and Shephard, 1995; Bauchau, Bottasso, and Nikishkov, 2001; Figure 9). DYMORE was a finite-element-based tool for analysis of nonlinear, flexible multibody systems, providing a general and flexible modeling approach that was modular and expandable. The multibody dynamics approach was needed to deal with complex mechanisms of arbitrary topology. The library of elements had rigid and deformable bodies, and joints, including a geometrically exact beam, without the approximations of modal reduction. The equations were solved for the static and dynamic response (by time integration) and stability (from linearized equations). The integration algorithm was designed for efficiency and robustness.

RotorCRAFT (Computation of Rotor Aerodynamics in Forward Flight) was developed by Continuum Dynamics, Inc. (Quackenbush, Bliss, Wachspress, Boschitsch, and Chua, 1990; Figure 10). In 1985–1987, EHPIC (Evaluation of Hover Performance using Influence Coefficients) was developed for the limited problem of free-wake analysis of rotors in hover and axial flight (Quackenbush, Bliss, and Wachspress, 1989). This code was followed by a more general analysis of rotors in forward flight, RotorCRAFT. The aerodynamic model was based on the forward flight wake of Bliss, Dadone, and Wachspress (1987), consisting of a full-span free wake constructed of curved vortex filaments along contours of constant vortex sheet strength, a natural representation of the wake that automatically accounts for both shed and trailed vorticity. A vortex lattice model of the blade gave the airloads, and a finite element blade structural model was used. The code solved for the periodic motion of an isolated rotor in steady flight. Quackenbush, Bliss, Boschitsch, and Wachspress (1992) added calculation of blade structural loads and hub loads, and coupled the analysis with noise calculations. Quackenbush, Lam, and Bliss (1994) modeled rotor/body interaction, using a panel model for the fuselage. Techniques to model the induced-loading and motion of vortex elements near a surface were developed.

CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model) was developed by Continuum Dynamics, Inc., by combining EHPIC and several extended versions of RotorCRAFT (Quackenbush, Wachspress, Boschitsch, and Curbishley, 1999; Wachspress, Quackenbush, and Boschitsch, 2003; Figure 10). CHARM is a comprehensive analysis applicable to a wide range of rotorcraft problems including wake/surface interaction, vibratory airloading, and noise generation. The aerodynamic model covered multiple rotors, wakes, and bodies, in free air and in an enclosure (including ground effect or a wind tunnel). Fast vortex and fast panel methods were used for a computationally efficient model, with a generalized periodic relaxation solution method for the full span wake in hover and low speed. The wake consisted of the full span, freely distorting, constant vorticity contour model. A lifting-surface vortex-lattice model of the blade was used, as well as lifting-line theory. Bodies were modeled with a lifting panel method. The solution procedure solved the aerodynamic and structural models in time for maneuvers, or iteratively for efficient convergence to the periodic solution of trim. The aperiodic solution of rotors operating at different rotational rates (main rotor and tail rotor) could be found. Quackenbush, Wachspress, Keller, Boschitsch, Wasileski, and Lawrence (2002) implemented a real-time version of CHARM, including the free-wake analysis.

UNITED KINGDOM DEVELOPMENTS

R-150 (Rotor Loads Program) was developed by Westland Helicopters (Hansford, 1979, 1986; Juggins, 1989; Figure 11). A predecessor was the rotor loads analysis R095 (1965–1974), which was based on the Houbolt and Brooks (1958) blade equations, modal analysis, and a vortex-ring wake model. An unsteady aerodynamics model was added in 1974–1980, and multiple load paths and fuselage upwash added in 1980–1982. The development of R-150 was started in 1982, with a new dynamic model and restructured software. The structural model was based on the nonlinear flap-lag-torsion equations of Hodges and Dowell (1974), modal analysis, section aerodynamics including dynamic stall and a wake of modified vortex rings from Beddoes (1976), and a unified formulation of structural loads for improved accuracy when using modal methods. The equations were solved by time integration.

CRFM (Coupled Rotor Fuselage Model) was developed by Westland Helicopters in cooperation with the Royal Aircraft Establishment (Juggins, 1989; Hansford, 1994; Figure 11). The objective was to predict rotor performance and loads and fuselage vibration in all flight conditions, both level and maneuvering flight, using a model of the coupled dynamics of the rotor and fuselage. This required extending the model to multiple blades, coupling the rotor and fuselage, and flying three-dimensional maneuvers. Development was initiated in 1985 with feasibility studies. The dynamic and aeroelastics theories were developed in 1987–1989. Development of the maneuvering wake model, solution methods, structural load methods, and pilot

simulation model occurred in 1989–1991. The Helicopter Manoeuvre Simulation Manager (HELMSMAN) code handled flying the maneuver by simulating the pilot; HELMSMAN was also used to achieve trim. The maneuvering wake model of Beddoes (1985) used large straight vortex elements with prescribed geometry that included the aircraft motion. The unsteady aerodynamics and dynamic stall model of Leishman and Beddoes (1989) was used. The blade structural model was similar to that of R-150, with the inclusion of coupled rotor-fuselage dynamics. Chan, Holton, and Hamm (1999) described the integration of the CRFM modules and the first demonstration of a symmetric pull-up maneuver. The theoretical approach was based on complex, coupled rotor-fuselage modes. This approach was explored in 1992–1993. For orthogonality of the complex modes, it was necessary to change from a transfer matrix to stiffness matrix method (1994). The computer storage requirements proved too large with complex modes, so branch modes were implemented in 1996 to couple the rotor and fuselage (with complex modes still an option when more computer memory became available). The first release of CRFM occurred in 1997, with evaluation of the symmetric pull-up in 1998 proving the capability of the code to calculate maneuvering rotor loads.

GERMAN DEVELOPMENTS

STAN (Stability Analysis) was developed by Messerschmitt-Bölkow-Blohm in the early 1970s (Figure 12). It originated with the DF55 code (created by H. Huber and his colleagues), which was the first complete helicopter simulation code at MBB. DF55 modeled the six aircraft degrees of freedom plus blade flap motion, simulating the Bo105 hingeless rotor blade using an equivalent offset hinge and a rigid blade (Reichert, 1973). For STAN, trim capability was added as well as additional rotor degrees of freedom (flap, lag, and two torsional motions). Concurrently, two specialized codes were developed: LEIRE (Leistungs Rechnung) for performance calculation, and BWVL for load calculation and real-time simulation. When computer hardware advances meant computation time for such analyses was less important, and there was increased collaboration among the disciplines of flight mechanics, loads, and performance calculation, the three codes were consolidated. From 1995 to 2005, first BWVL and then LEIRE were integrated with STAN to produce a single calculation tool called GENSIM. GENSIM was Eurocopter's in-house helicopter simulation tool for global steady and unsteady performance, flight mechanics, and loads calculations (Dietz, Maucher, and Schimke, 2010). The blade aerodynamic model was based on blade element/momentum theory with simple analytical downwash models and rigid blades.

S4 (4th generation rotor Simulation program) was a high-resolution rotor simulation tool developed by the German Aerospace Center (DLR) for investigations of rotor dynamics, vibration and noise reduction, dynamic stall, blade airloads, and performance (Figure 13). In the mid-

1970s, the new helicopter branch at the German Test and Research Institute for Aviation and Space Flight (DFVLR) needed a rotor simulation for an investigation of higher-harmonic control. The first version of the code was produced in 1976, implementing a simple blade-element model with rigid and first elastic flap motion, the induced velocity of Mangler and Squire (1950), and tabular section aerodynamics. Time integration of the equations of motions was used, with trim to desired thrust and hub moments. This development stage was finished by 1980, including addition of the first torsion mode, and the code was used in higher-harmonic control investigations in the 1980s. S2 (2nd generation), developed in 1986–1987, included a finite element model of the blades for better representation of hingeless rotor dynamics and the unsteady aerodynamic model of Leiss (1984). The S3 variant in 1989 included fuselage interference at the rotor disk. Introduction of a prescribed wake model based on an extension of Beddoes (1985), refinements of the solution method, and the first user's guide in 1990 produced S4 (van der Wall, 1992). Motivated by the HART wind tunnel test, in 1994 the prescribed wake underwent a major upgrade to account for deflections caused by harmonic blade loading. In parallel, a free-wake code for use in loose coupling was developed (van der Wall and Roth, 1997).

SIMH was developed at DLR as a flight simulation analysis (Figure 14). Through a cooperative program between NASA Ames Research Center and DLR, the SIM code for fixed-wing aircraft was developed by D. B. Mackie in the early 1980s. D. B. Mackie and W. von Grünhagen introduced a nonlinear helicopter model to the SIM kernel, producing the SIMH code. The first complete helicopter simulation code was available at DLR in 1984, followed by a process of continuing improvement. DLR performed several flight test campaigns with a Bo-105 research helicopter to generate a comprehensive flight test database, with the first SIMH validation report in 1986. The code was extended for open loop and inverse simulation analysis (Gray and von Grünhagen, 1994), and a hybrid inflow model to handle aircraft pitch and roll cross-coupling was introduced (von Grünhagen, 1995). For transfer of the code to a new computer environment in 1996, the main rotor and engine components were restructured, and the aerodynamic model updated. A derivative of SIMH was implemented on the DLR real-time simulator. To meet external requirements for real-time simulations, a platform-independent SIMH version was produced. The simulation sequence of trim and integration routines was further optimized for real-time application, tools only used for research purposes were removed, and a clear distinction was made between modeling code and helicopter configuration data. The code was made available to industry in 1999, and a user's guide was written. In 2000, when DLR and ONERA initiated a common rotorcraft research program, the development of SIMH was stopped so work would focus on the development of the HOST code.

FRENCH DEVELOPMENTS

R85 was developed in 1980 by the Aérospatiale Helicopter Division (Allongue and Krynski, 1990; Figure 14). Early codes used simplified models, and had convergence issues and poor software practices. There were separate codes for loads and vibration and for aeroelastic stability, with different models and different input. The new comprehensive analysis R85 was developed by aerodynamicists (for loads) and dynamicists (for stability) to calculate performance, loads, vibration, and stability for an isolated rotor, including articulated, hingeless, and bearingless configurations. The R85 blade model could be rigid or elastic, with simple inflow or the METAR vortex wake (Arnaud and Beaumier, 1992). For trim, a harmonic representation of the motion was obtained. For stability, linearized equations were analyzed.

HOST

HOST (Helicopter Overall Simulation Tool) was developed initially by Aérospatiale (Benoit, Dequin, Kampa, von Grunhagen, Basset, and Gimonet, 2000; Figure 14). Attempts to use the R85 blade model for extended simulation with the S80 flight simulation code proved difficult so, in the early 1990s, a requirement for a new comprehensive analysis was defined for a consistent treatment of handling qualities, stability, and loads calculations. HOST covered the trim, transient, and flutter tasks. For trim, a harmonic representation of the motion was used, with a Newton method to achieve the flight condition. For the transient task, the equations were integrated in time. For flutter, linearized equations were analyzed. When MBB and Aérospatiale merged to form Eurocopter, harmonization of tools for aeromechanics studies led to HOST as the common tool. The research establishments also contributed, DLR bringing the technologies of the SIMH flight simulation program, and ONERA bringing rotor aerodynamics and induced velocity models. The HOST code encompassed different model levels from disk plus linear inflow to elastic blade plus vortex wake, and from isolated rotor to a full helicopter or tiltrotor simulation, with the capability to handle new rotor and aircraft configurations.

CAMRAD II

CAMRAD II was developed by Johnson Aeronautics (Johnson, 1994, 1998a; Figure 7). CAMRAD II was an aeromechanical analysis of helicopters and rotorcraft that incorporated a combination of advanced technology, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics, with an input-driven definition of the configuration geometry and topology. Many of the limitations of first generation analyses were found in CAMRAD/JA. CAMRAD/JA had fixed geometry, dynamic, and aerodynamic models. The structural dynamic and aerodynamic models were mixed. There was only one solution method, and the solution procedures and physical models were mixed. It was not possible to change one part of the analysis without considering the entire code. The

blade model assumed a single load path. The rotor model had one rotating-to-nonrotating interface at the hub node, without a swashplate node, so the control system load path was not rigorously modeled. Small dynamic motion was assumed, although high inflow and large angles were considered in the aerodynamic model. The transient analysis assumed quasistatic rotor motion. Recent theoretical developments for beams, wakes, and wake geometry were not utilized. The capabilities and limitations of CAMRAD/JA provided the requirements for an entirely new analysis.

Development of CAMRAD II began in 1989, with the first release in 1993 (Figure 7), after an effort of 5 man-years. Release 2.0 in 1996 added a general free-wake geometry and multiple trailer wake model (Johnson, 1995), and a beam element modeling composite, as well as isotropic materials with geometrically exact elastic motion (Johnson, 1998b). Release 3.0 in 1997 improved the unsteady aerodynamic and dynamic stall representation in the wing component, and improved the hover free wake (Johnson, 1998c). Release 4.0 occurred in 2000, and release 4.9 in 2012; the total development effort has been about 12 man-years. CAMRAD II was based on a combination of multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics. Multibody dynamics provided rigid body components, frames, joints, and nonlinear kinematics. Structural dynamics technology provided substructure coupling and static residuals, modal analysis and truncation, and the approach for elimination of constraints. Finite element technology provided nonlinear elements, numerical integration, and beam components. Rotorcraft aeromechanics provided aircraft dynamics, rotating systems, and aerodynamics. The mathematical model allowed structural, aerodynamic, and kinematic nonlinearities, and arbitrary large motion, including rigid body motions and large rotations of components relative to each other. So CAMRAD II could model the true geometry of a rotorcraft, including multiple load paths such as a swashplate and control system, lag dampers, tension/torsion straps, and bearingless rotors. CAMRAD II used a building-block approach to achieve flexibility in the model of the dynamic and aerodynamic configuration, and in the solution procedure. Separating the specification of the configuration, the aeromechanical model, and the solution procedure was essential for expandability of the analysis. The building-block approach also led naturally to more general and more rigorous models. A flexible analysis required a large amount of detailed input information, so for ease of use CAMRAD II could construct typical rotor and rotorcraft configurations using a higher level of input. The detailed input capability was still available, so the model could be defined and revised for new and unique configurations.

OBSERVATIONS

A number of common themes emerge from this history. The development of comprehensive analyses began as soon as digital computers first became available to engineers in

the 1960s, for rotor design was severely limited by the simplifying assumptions required for practical analyses up to that time. From the beginning, the focus was on flight dynamics and structural loads, requiring models of the aerodynamics, dynamics, and structure of the entire aircraft. The subject of the 1973 AGARD meeting and the 1974 AHS meeting was rotor loads.

The codes of the 1970s are considered the first generation of helicopter comprehensive analyses. They exhibited a number of common limitations. Codes were restricted in the range of helicopter and rotor configurations, and the range of analysis. New configurations required developing new equations of motion. Software development processes were poor, documentation was absent, and upgrades and maintenance were difficult. Recently available technology was used neither uniformly nor well.

Major new codes were developed beginning in the 1980s, often in direct response to the recognition of these limitations. The emphasis was on flexibility and versatility through theory using assembly of primitive substructures, modular and structured software architecture, and modern software development methodology. In many cases the approach was to start by restructuring a first-generation code, with reduction in cost and development time, simplified validation, and early achievement of the required capabilities.

Finite elements are needed to model the complexity of rotor structures, and finite element models were developed for rotor blade analysis in the early 1980s. Multibody dynamics technology is needed to model the mechanisms found in rotors. Finite element and multibody dynamics modeling capability, including input-driven definition of the geometry, was fully integrated into comprehensive analyses in the 1990s.

Significant attention was given in the 1990s and 2000s to rotor aerodynamics, including wakes and wake geometry. Methods for coupling CFD codes with rotorcraft comprehensive analyses, with the latter handling all structural dynamic response and aircraft trim and trajectory calculations, matured in the 2000s. Versions of comprehensive analyses that can be executed in real time have been demonstrated. Current activities recognize that there is still the need for reliable and efficient calculation of structural loads and vibration in the extremes of the aircraft operating capability.

Current comprehensive analyses are based on beam models of the blade structure, lifting-line models of the blade aerodynamics, and vortex wake models. The structural dynamics are modeled using finite elements and multibody dynamics, giving exact geometry and kinematics with the capability to represent arbitrary designs. The comprehensive analysis can be coupled with CFD codes to better calculate airloads. The code input allows description of arbitrary geometry and configurations.

The next generation of rotorcraft comprehensive analyses will be driven and enabled by the tremendous capabilities of high-performance computing (Johnson and Datta, 2008), which offers the opportunity for major expansion of rotorcraft analysis and design capability. Experience with current codes clearly defines the requirements for the next generation of comprehensive analyses. As usual, rotorcraft calculations demand the widest possible integration of disciplines, a fact that makes comprehensive analyses challenging and keeps the development interesting.

ACKNOWLEDGMENTS

This survey has been based largely on published descriptions of rotorcraft comprehensive analyses. Lost to history are internal code developments, particularly in industry, that never received documentation in the open literature. Important suggestions and recollections were received from many of the people involved in the code developments: Richard Bennett, Bernard Benoit, Inderjit Chopra, John Davis, Ronald Du Val, Robert Hansford, Philip Jiggins, Andrew Kerr, Robert Ormiston, Todd Quackenbush, Arthur Ragosta, Hossein Saberi, Dieter Schimke, Louis Silverthorn, Robert Sopher, Berend van der Wall, and Wolfgang von Gruenhagen.

REFERENCES

- Allongue, M., and Kryszinski, T., "Validation of a New General Aérospatiale Aeroelastic Rotor Model Through the Wind Tunnel and Flight Tests Data," American Helicopter Society 46th Annual Forum, Washington, DC, May 1990.
- Arcidiacono, P.J., "Prediction of Rotor Instability at High Forward Speeds. Volume I. Steady Flight Differential Equations of Motion for a Flexible Helicopter Blade with Chordwise Mass Unbalance," USAAVLABS TR 68-18A, February 1969.
- Arcidiacono, P.J., and Carlson, R.G., "Helicopter Rotor Loads Prediction," AGARD CP 122, March 1973.
- Arcidiacono, P.J.; Carta, F.O.; Casellini, L.M.; and Elman, H.L., "Investigation of Helicopter Control Loads Induced by Stall Flutter," USAAVLABS TR 70-2, March 1970.
- Arnaud, G., and Beaumier, P., "Validation of R85/METAR on the Puma RAE Flight Tests," Eighteenth European Rotorcraft Forum, Avignon, France, Sept., 1992.
- Austin, E.E., and Vann, W.D., "General Description of the Rotorcraft Flight Simulation Computer Program (C-81)," USAAMRDL TN 11, June 1973.
- Bagai, A., and Leishman, J.G., "Rotor Free-Wake Modeling Using a Pseudo-Implicit Technique—Including Comparisons with Experimental Data," *Journal of the American Helicopter Society*, Vol. 40, No. 3, July 1995, pp. 29–41.
- Bauchau, O.A.; Bottasso, C.L.; Dindar, M.; Murty, H.S.; Rusak, Z.; and Shephard, M.S., "Aeroelastic Stability of Rotor Blades Using A Parallel Adaptive Finite Element Solver," American Helicopter Society 2nd International Aeromechanics Specialists' Conference, Bridgeport, CT, October 1995.
- Bauchau, O.A.; Bottasso, C.L.; and Nikishkov, Y.G., "Modeling Rotorcraft Dynamics with Finite Element Multibody Procedures," *Mathematical and Computer Modeling*, Vol. 33, No. 10–11, May–June 2001.
- Beddoes, T.S., "A Synthesis of Unsteady Aerodynamic Effects Including Stall Hysteresis," *Vertica*, Vol. 1, No. 2, 1976, pp. 113–123.
- Beddoes, T.S., "A Wake Model for High Resolution Airloads," American Helicopter Society International Conference on Rotorcraft Basic Research, Research Triangle Park, NC, February 1985.
- Bennett, R.L., "Rotor System Design and Evaluation Using a General Purpose Helicopter Flight Simulation Program," AGARD CP 122, March 1973.
- Bennett, R.L., and Blankenship, B.L., "Rotorcraft Flight Simulation with Aeroelastic Rotor Representation," USAAMRDL TR 71-68, 1972.
- Benoit, B.; Dequin, A.-M.; Kampa, K.; von Grunhagen, W.; Basset, P.-M.; and Gimonet, B., "HOST, A General Helicopter Simulation Tool for Germany and France," American Helicopter Society 56th Annual Forum, Virginia Beach, VA, May 2000.
- Bergquist, R.R., "Helicopter Gust Response Including Unsteady Aerodynamic Stall Effects," USAAMRDL TR 72-68, May 1973.
- Bhagwat, M.J., and Leishman, J.G., "Stability, Consistency and Convergence of Time-Marching Free-Vortex Rotor Wake Algorithms," *Journal of the American Helicopter Society*, Vol. 46, No. 1, January 2001, pp. 59–71.
- Bhagwat, M.J., and Leishman, J.G., "Rotor Aerodynamics During Maneuvering Flight Using a Time-Accurate Free-Vortex Wake," *Journal of the American Helicopter Society*, Vol. 48, No. 3, July 2003, pp. 143–158.
- Bir, G., and Chopra, I., "Status of University of Maryland Advanced Rotorcraft Code," American Helicopter Society Aeromechanics Specialists Conference, San Francisco, CA, January 1994.
- Bir, G.; Chopra, I.; and Nguyen, K., "Development of UMARC (University of Maryland Advanced Rotorcraft Code)," American Helicopter Society 46th Annual Forum, Washington, DC, May 1990.
- Blankenship, B.L., and Bird, B.J., "Program C81-11 Rotorcraft Flight Simulation," Bell Helicopter Company, BHC Report 599-068-900, January 1967.
- Blankenship, B.L., and Harvey, K.W., "A Digital Analysis for Helicopter Performance and Rotor Blade Bending Moments," *Journal of the American Helicopter Society*, Vol. 7, No. 4, October 1962, pp. 55–69.
- Bliss, D.B.; Dadone, L.; and Wachspress, D.A., "Rotor Wake Modeling for High Speed Applications," American Helicopter Society 43rd Annual Forum, St. Louis, MO, May 1987.

- Bourtsev, B.N.; Selemenov, S.V.; and Vagis, V.P., "Coaxial Helicopter Rotor Design and Aeromechanics," Twenty-Fifth European Rotorcraft Forum, Rome, Italy, September 1999.
- Briczinski, S.J., "Validation of the Rotorcraft Flight Simulation Program (C81) for Articulated Rotor Helicopters Through Correlation with Flight Data," USAAMRDL TR 76-4, May 1976.
- Burtsev, B.N., "Aeroelasticity of a Coaxial Helicopter Rotor," Seventeenth European Rotorcraft Forum, Berlin, Germany, September 1991.
- Callahan, C.B., and Bassett, D.E., "Application of a Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) to the McDonnell Douglas AH-64A Helicopter," NASA CR 177455, November 1988.
- Carlson, R.M., and Kerr, A.W., "Integrated Rotor/Body Loads Prediction," AGARD CP 122, March 1973.
- Chan, W.Y.F.; Holton, S.A.; and Hamm, J.C., "Results of Initial Aircraft Manoeuvre Simulation on the Coupled Rotor Fuselage Model (CRFM)," American Helicopter Society 55th Annual Forum, Montreal, Canada, May 1999.
- Computer Sciences Corporation, "The Predesign Phase of the Second-Generation Comprehensive Helicopter Analysis System," USARTL TR 78-41, October 1978.
- Control Data Corporation, "Predesign of the Second-Generation Comprehensive Helicopter Analysis System," USARTL TR 78-43, October 1978.
- Corrigan, J.J.; Schillings, J.J.; Yin, S.K.; and Hsieh, P.Y., "Developments in Dynamics Methodology at Bell Helicopter Textron," American Helicopter Society 44th Annual Forum, Washington, DC, June 1988.
- Corrigan, J.J.; Bennett, R.L.; and Hsieh, P.Y., "COPTER 2000: The QTR and Beyond," American Helicopter Society 57th Annual Forum, Washington, DC, May 2001.
- Corrigan, J.J.; Meyer, A.; Bothwell, M.; and Brown, H., "Computer Flight Testing of Rotorcraft," American Helicopter Society Vertical Lift Aircraft Design Conference, San Francisco, CA, January 2006.
- Crawford, C.C., Jr., "Rotorcraft Analytical Improvement Needed to Reduce Development Risk," *Journal of the American Helicopter Society*, Vol. 35, No. 1, January 1990, pp. 3–22.
- Davis, J.M.; Bennett, R.L.; and Blankenship, B.L., "Rotorcraft Flight Simulation with Aeroelastic Rotor and Improved Aerodynamic Representation," USAAMRDL TR 74-10, June 1974.
- Dietz, M.; Maucher, C.; and Schimke, D., "Addressing Today's Aeromechanic Questions by Industrial Answers," American Helicopter Society Specialists' Conference on Aeromechanics, San Francisco, CA, January 2010.
- Duhon, J.M.; Harvey, K.W.; and Blankenship, B.L., "Computer Flight Testing of Rotorcraft," *Journal of the American Helicopter Society*, Vol. 10, No. 4, October 1965, pp. 36–48.
- Du Val, R.W., "A Real-Time Blade Element Helicopter Simulation For Handling Qualities Analysis," Fifteenth European Rotorcraft Forum, Amsterdam, The Netherlands, September 1989.
- Du Val, R.W., "A Low Cost—High Fidelity Real-Time Rotorcraft Simulation for Control and Handling Qualities Analysis," HeliJapan 1998: AHS International Meeting on Rotorcraft Technology and Disaster Relief, Gifu, Japan, April 1998.
- Du Val, R.W., "A Real-Time Multi-Body Dynamics Architecture for Rotorcraft Simulation," American Helicopter Society and Royal Aeronautical Society International Conference on The Challenge of Realistic Rotorcraft Simulation, London, UK, November 2001.
- Freeman, F.D., and Bennett, R.L., "Application of Rotorcraft Flight Simulation Program (C81) to Predict Rotor Performance and Bending Moments for a Model Four-Bladed Articulated Rotor System," USAAMRDL TR 74-70, November 1974.
- Gabel, R., "Current Loads Technology for Helicopter Rotors," AGARD CP 122, March 1973.
- Ghiringhelli, G.L.; Masarati, P.; Mantegazza, P.; and Nixon, M.W., "Multi-Body Analysis of the 1/5 Scale Wind Tunnel Model of the V-22 Tiltrotor," American Helicopter Society 55th Annual Forum, Montreal, Canada, May 1999.
- Gray, G.J., and von Grünhagen, W., "An Investigation of Open Loop and Inverse Simulation as Nonlinear Model Validation Tools for Helicopter Flight Mechanics," Royal Aeronautical Society Conference on Rotorcraft Simulation, London, UK, May 1994.
- Hamrick, T.; Copland, D.; Tarzanin, F.; Staley, J.; Hunt, L.; and Burns, G., "Predesign of the Second Generation Comprehensive Helicopter Analysis System," USARTL TR 78-42, December 1978.
- Hansford, R.E., "Comparison of Predicted and Experimental Rotor Loads to Evaluate Flap-Lag Coupling with Blade Pitch," *Journal of the American Helicopter Society*, Vol. 24, No. 5, October 1979, pp. 3–11.
- Hansford, R.E., "A Unified Formulation of Rotor Load Prediction Methods," *Journal of the American Helicopter Society*, Vol. 31, No. 2, April 1986, pp. 58–65.
- Hansford, R.E., "Considerations in the Development of the Coupled Rotor Fuselage Model," *Journal of the American Helicopter Society*, Vol. 39, No. 4, October 1994, pp. 70–81.
- Harris, F.D.; Tarzanin, F.J., Jr.; and Fisher, R.K., Jr., "Rotor High Speed Performance, Theory vs. Test," *Journal of the American Helicopter Society*, Vol. 15, No. 3, July 1970, pp. 35–44.
- Harvey, K.W.; Blankenship, B.L.; and Drees, J.M., "Analytical Study of Helicopter Gust Response at High Forward Speeds," USAAVLABS TR 69-1, September 1969.
- Hodges, D.H., and Dowell, E.H., "Nonlinear Equations of Motion for the Elastic Bending and Torsion of Twisted

- Nonuniform Rotor Blades," NASA TN D-7818, December 1974.
- Houbolt, J.C., and Brooks, G.W., "Differential Equations of Motion for Combined Flapwise Bending, Chordwise Bending, and Torsion of Twisted Nonuniform Rotor Blades," NACA Report 1346, 1958.
- Howlett, J.J., "UH-60A Black Hawk Engineering Simulation Program," NASA CR 166309, CR 166310, December 1981.
- Johnson, W., "The Effect of Dynamic Stall on the Response and Airloading of Helicopter Rotor Blades," *Journal of the American Helicopter Society*, Vol. 14, No. 2, April 1969, pp. 68–79.
- Johnson, W., "A Lifting Surface Solution for Vortex Induced Airloads and Its Application to Rotary Wing Airloads Calculations," NASA CR 192328, April 1970.
- Johnson, W., "Aeroelastic Analysis for Rotorcraft in Flight or in a Wind Tunnel," NASA TN D-8515, July 1977.
- Johnson, W., "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics," NASA TM 81182, NASA TM 81183, NASA TM 81184, June 1980.
- Johnson, W., "Development of a Comprehensive Analysis for Rotorcraft," *Vertica*, Vol. 5, No. 2, 1981, pp. 99–129, and Vol. 5, No. 3, 1981, pp. 185–216.
- Johnson, W., "CAMRAD/JA. A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Johnson Aeronautics Version," Johnson Aeronautics, Palo Alto, CA, 1988.
- Johnson, W., "Wake Model for Helicopter Rotors in High Speed Flight," NASA CR 177507, November 1988.
- Johnson, W., "Technology Drivers in the Development of CAMRAD II," American Helicopter Society Aeromechanics Specialists Conference, San Francisco, CA, January 1994.
- Johnson, W., "A General Free Wake Geometry Calculation for Wings and Rotors," American Helicopter Society 51st Annual Forum, Ft. Worth, TX, May 1995.
- Johnson, W., "Rotorcraft Aeromechanics Applications of a Comprehensive Analysis," HeliJapan 1998: AHS International Meeting on Rotorcraft Technology and Disaster Relief, Gifu, Japan, April 1998a.
- Johnson, W., "Rotorcraft Dynamics Models for a Comprehensive Analysis," American Helicopter Society 54th Annual Forum, Washington, DC, May 1998b.
- Johnson, W., "Rotorcraft Aerodynamic Models for a Comprehensive Analysis," American Helicopter Society 54th Annual Forum, Washington, DC, May 1998c.
- Johnson, W., and Datta, A., "Requirements for Next Generation Comprehensive Analysis of Rotorcraft," American Helicopter Society Specialists' Conference on Aeromechanics, San Francisco, CA, January 2008.
- Juggins, P.T.W., "Application of the Westland CRFD Program to Total Helicopter Dynamics," American Helicopter Society National Specialists' Meeting on Rotorcraft Dynamics, Arlington, TX, November 1989.
- Kerr, A.W., and Davis, J.M., "A System For Interdisciplinary Analysis—A Key to Improved Rotorcraft Design," American Helicopter Society 35th Annual Forum, Washington, DC, May 1979.
- Kerr, A.W.; Potthast, A.J.; and Anderson, W.D., "An Interdisciplinary Approach to Integrated Rotor/Body Mathematical Modeling," American Helicopter Society Symposium on the Status of Testing and Modeling Techniques for V/STOL Aircraft, Essington, PA, October 1972.
- Kerr, A.W., and Stephens, W.B., "The Development of a System for Interdisciplinary Analysis of Rotorcraft Flight Characteristics," AGARD CP 334, May 1982.
- Landgrebe, A.J., "An Analytical Method for Predicting Rotor Wake Geometry," *Journal of the American Helicopter Society*, Vol. 14, No. 4, October 1969, pp. 20–32.
- Landgrebe, A.J., and Egolf, T.A., "Rotorcraft Wake Analysis for the Prediction of Induced Velocities," USAAMRDL TR 75-45, January 1976.
- Leishman, J.G., and Beddoes, T.S., "A Semi-Empirical Model for Dynamic Stall," *Journal of the American Helicopter Society*, Vol. 34, No. 3, July 1989, pp. 3–17.
- Leiss, U., "A Consistent Mathematical Model to Simulate Steady and Unsteady Rotor-Blade Aerodynamics," Tenth European Rotorcraft Forum, The Hague, The Netherlands, August 1984.
- Lemnios, A.Z., "Rotary Wing Design Methodology," AGARD CP 122, March 1973.
- Lemnios, A.Z., and Smith, A.F., "An Analytical Evaluation of the Controllable Twist Rotor Performance and Dynamic Behavior," USAAMRDL TR 72-16, May 1972.
- Lim, J.W.; Panda, B.; Sopher, R.; Cassarino, S.J.; and Lee, C.S., "Current Status of U.S. Army Comprehensive Helicopter Analysis System," American Helicopter Society 56th Annual Forum, Virginia Beach, VA, May 2000.
- Livingston, C.L.; Bird, B.J.; and McLarty, T.T., "A Stability and Control Prediction Method for Helicopters and Stoppable Rotor Aircraft," AFFDL TR 69-123, February 1970.
- Mangler, K.W., and Squire, H.B., "The Induced Velocity Field of a Rotor," ARC R&M 2642, May 1950.
- McLarty, T.T.; Van Gaasbeek, J.R.; and Hsieh, P.Y., "Rotorcraft Flight Simulation with Coupled Rotor Aeroelastic Stability Analysis," USAAMRDL TR 76-41, May 1977.
- Neff, J.R., "Integrating Dynamic Analysis and Helicopter Design," NASA SP-352, February 1974.
- Ormiston, R.A., "Comparison of Several Methods for Predicting Loads on a Hypothetical Helicopter Rotor," NASA SP-352 (February 1974) and *Journal of the American Helicopter Society*, Vol. 19, No. 4, October 1974, pp. 2–13.
- Ormiston, R.A.; Rutkowski, M.J.; Ruzicka, G.C.; Saberi, H.; and Jung, Y.C., "Comprehensive Aeromechanics Analysis of Complex Rotorcraft Using 2GCHAS," American Helicopter

- Society Aeromechanics Specialists Conference, San Francisco, CA, January 1994.
- Peters, D.A., and He, C.J., "Finite State Induced Flow Models. Part II: Three-Dimensional Rotor Disk," *Journal of Aircraft*, Vol. 32, No. 2 (March–April 1995), pp. 323–333.
- Phelan, P.G., and Tarzanin, F.J., Jr., "Restructuring the Rotor Analysis Program C-60," American Helicopter Society 2nd Decennial Specialists' Meeting On Rotorcraft Dynamics, Moffett Field, CA, November 1984 (NASA CP 2400, November 1985).
- Piziali, R.A., and DuWaldt, F.A., "A Method for Computing Rotary Wing Airload Distribution in Forward Flight," TCRC TR 62-44, November 1962.
- Quackenbush, T.R.; Bliss, D.B.; Boschitsch, A.H.; and Wachspress, D.A., "Analysis of Rotor Vibratory Loads Using Higher Harmonic Control," NASA CR 189591, April 1992.
- Quackenbush, T.R.; Bliss, D.B.; and Wachspress, D.A., "New Free-Wake Analysis of Rotorcraft Hover Performance Using Influence Coefficients," *Journal of Aircraft*, Vol. 26, No. 12, December 1989, pp. 1090–1097.
- Quackenbush, T.R.; Bliss, D.B.; Wachspress, D.A.; Boschitsch, A.H.; and Chua, K., "Computation of Rotor Aerodynamic Loads in Forward Flight Using a Full-Span Free Wake Analysis," NASA CR 177611, December 1990.
- Quackenbush, T.R.; Lam, C.-M.G.; and Bliss, D.B., "Vortex Methods for the Computational Analysis of Rotor/Body Interaction," *Journal of the American Helicopter Society*, Vol. 39, No. 4, October 1994, pp. 14–24.
- Quackenbush, T.R.; Wachspress, D.A.; Boschitsch, A.H.; and Curbishley, T.B., "A Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) for General Rotor/Surface Interaction," CDI Report 99-03, January 1999.
- Quackenbush, T.R.; Wachspress, D.A.; Keller, J.D.; Boschitsch, A.H.; Wasileski, B.J.; and Lawrence, T.H., "Full Vehicle Flight Simulation with Real Time Free Wake Methods," American Helicopter Society Aerodynamics, Acoustics, and Test and Evaluation Technical Specialists' Meeting, San Francisco, CA, January 2002.
- Quaranta, G.; Bindolino, G.; Masarati, P.; and Mantegazza, P., "Toward a Computational Framework for Rotorcraft Multi-Physics Analysis: Adding Computational Aerodynamics to Multibody Rotor Models," Thirtieth European Rotorcraft Forum, Marseilles, France, September 2004.
- Reichert, G., "Loads Prediction Methods for Hingeless Rotor Helicopters," AGARD CP 122, March 1973.
- Rutkowski, M.J.; Ruzicka, G.C.; Tan, C.M.; Ormiston, R.A.; and Stephens, W.B., "First Level Release of 2GCHAS for Comprehensive Helicopter Analysis—A Status Report," American Helicopter Society International Technical Specialists' Meeting on Rotorcraft Basic Research, Atlanta, GA, March 1991.
- Saberi, H.-A.; Jung, Y.C.; and Anastassiades, T., "Finite Element and Modal Method in Multibody Dynamic Code," American Helicopter Society 2nd International Aeromechanics Specialists' Conference, Bridgeport, CT, October 1995.
- Saberi, H.; Khoshlahjeh, M.; Ormiston, R.A.; and Rutkowski, M.J., "Overview of RCAS and Application to Advanced Rotorcraft Problems," American Helicopter Society 4th Decennial Specialists' Conference on Aeromechanics, San Francisco, CA, January 2004.
- Saberi, H.; Tang, K.; Ware, C.; and English, J., "Numerically Efficient Rotorcraft Trim and Transient Response," USAAMCOM TR 00-D-13, May 2000.
- Sadler, S.G., "Development and Application of a Method for Predicting Rotor Free Wake Positions and Resulting Rotor Blade Air Loads," NASA CR 1911, NASA CR 1912, December 1971.
- Sangha, K.B., "Bearingless Rotors and Higher Harmonic Control Modeling Using RACAP," American Helicopter Society 44th Annual Forum, Washington, DC, June 1988.
- Sangha, K.B.; Weisenburger, R.K.; and Straub, F.K., "Rotor/Airframe Aeroelastic Analyses Using the Transfer Matrix Approach," AIAA Paper 90-1119, April 1990.
- Sangha, K., and Straub, F., "A Case Study in Multi-Component Software Development," AIAA Paper 91-1205, April 1991.
- Scully, M.P., "Computation of Helicopter Rotor Wake Geometry and Its Influence on Rotor Harmonic Airloads," MIT ASRL TR 178-1, March 1975.
- Shultz, L.A.; Panda, B.; Tarzanin, F.J.; Derham, R.C.; Oh, B.K.; and Dadone, L., "Interdisciplinary Analysis for Advanced Rotors—Approach, Capabilities and Status," American Helicopter Society Aeromechanics Specialists Conference, San Francisco, CA, January 1994.
- Silverthorn, L.J., "Whirl Mode Stability of the Main Rotor of the YAH-64 Advanced Attack Helicopter," American Helicopter Society 38th Annual Forum, Anaheim, CA, May 1982.
- Simpson, J.R., "Preliminary Design of a Rotor System for a Hot Cycle Heavy-Lift Helicopter," USAAVLABS TR 67-1, March 1967.
- Sivaneri, N.T., and Chopra, I., "Dynamic Stability of a Rotor Blade Using Finite Element Analysis," *AIAA Journal*, Vol. 20, No. 5, May 1982, pp. 716–723.
- Sivaneri, N.T., and Chopra, I., "Finite Element Analysis for Bearingless Rotor Blade Aero-elasticity," *Journal of the American Helicopter Society*, Vol. 29, No. 2, April 1984, pp. 42–51.
- Sopher, R., "Recent Developments in Rotor Dynamics Methodology in the U.S. Industry," American Helicopter Society National Specialists' Meeting on Rotorcraft Dynamics, Arlington, TX, November 1989.
- Sopher, R., and Hallock, D.W., "Time-History Analysis for Rotorcraft Dynamics Based on a Component Approach,"

- Journal of the American Helicopter Society*, Vol. 31, No. 1, January 1986, pp. 43–51.
- Sopher, R.; Studwell, R.E.; Cassarino, S.; and Kottapalli, S.B.R., "Substructure Program for Analysis of Helicopter Vibrations," *Journal of the American Helicopter Society*, Vol. 28, No. 4, October 1983, pp. 14–21.
- Staley, J.A., "Validation of Rotorcraft Flight Simulation Program Through Correlation with Flight Data for Soft-In-Plane Hingeless Rotors," USAAMRDL TR 75-50, January 1976.
- Stephens, W.B.; Rutkowski, M.J.; Ormiston, R.A.; and Tan, C.M., "Development of the Second Generation Comprehensive Helicopter Analysis System (2GCHAS)," American Helicopter Society National Specialists' Meeting on Rotorcraft Dynamics, Arlington, TX, November 1989.
- Tanner, W.H., "Charts for Estimating Rotary Wing Performance in Hover and at High Forward Speeds," NASA CR 114, November 1964.
- Tarzanin, F.J., Jr., "Prediction of Control Loads Due to Blade Stall," *Journal of the American Helicopter Society*, Vol. 17, No. 2, April 1972, pp. 33–46.
- van der Wall, B., "Analytic Formulation of Unsteady Profile Aerodynamics and Its Application to Simulation of Rotors," ESA TT 1244, August 1992.
- van der Wall, B.G., and Roth, M., "Free-Wake Analysis on Massively Parallel Computers and Validation with HART Test Data," American Helicopter Society 53rd Annual Forum, Virginia Beach, VA, May 1997.
- Van Gaasbeek, J.R., "An Investigation of High-G Maneuvers of the AH-1G Helicopter," USAAMRDL TR 75-18, April 1975.
- Van Gaasbeek, J.R., "Validation of the Rotorcraft Flight Simulation Program (C81) Using Operational Loads Survey Flight Test Data," USAAVRADCOM TR 80-D-4, July 1980.
- Van Gaasbeek, J.R., and Hsieh, P.Y., "Rotorcraft Flight Simulation Computer Program C81 with DATAMAP Interface," USAAVRADCOM TR 80-D-38, October 1981.
- Van Gaasbeek, J.R.; McLarty, T.T.; Sadler, S.G.; and Hsieh, P.Y., "Rotorcraft Flight Simulation, Computer Program C81," USARTL TR 77-54, October 1979.
- Vann, W.D.; Mirick, P.H.; and Austin, E.E., "Use of Computer Math Models for Aircraft Evaluation," USAAMRDL TN 12, August 1973.
- von Grünhagen, W., "Dynamic Inflow Modelling for Helicopter Rotors and Its Influence on the Prediction of Crosscoupling," American Helicopter Society 2nd International Aeromechanics Specialists' Conference, Bridgeport, CT, October 1995.
- Wachspress, D.A.; Quackenbush, T.R.; and Boschitsch, A.H., "First-Principles Free-Vortex Wake Analysis for Helicopters and Tiltrotors," American Helicopter Society 59th Annual Forum, Phoenix, AZ, May 2003.
- Yang, W.-D.; Zhang, C.-L.; and Wang, S.-C., "Aeroelastic Analysis of Helicopter Rotor Blade With Advanced Tips and Trailing Edge Flaps," Twenty-Second European Rotorcraft Forum, Brighton, UK, September 1996.
- Yavrucuk, I.; Tarimci, O.; Katircioglu, M.; Kubali, E.; and Yilmaz, D., "A New Helicopter Simulation and Analysis Tool: Helidyn+," Thirty-Sixth European Rotorcraft Forum, Paris, France, September 2010.
- Yen, J.G.; Corrigan, J.J.; Schillings, J.J.; and Hsieh, P.Y., "Comprehensive Analysis Methodology at Bell Helicopter: COPTER," American Helicopter Society Aeromechanics Specialists Conference, San Francisco, CA, January 1994.

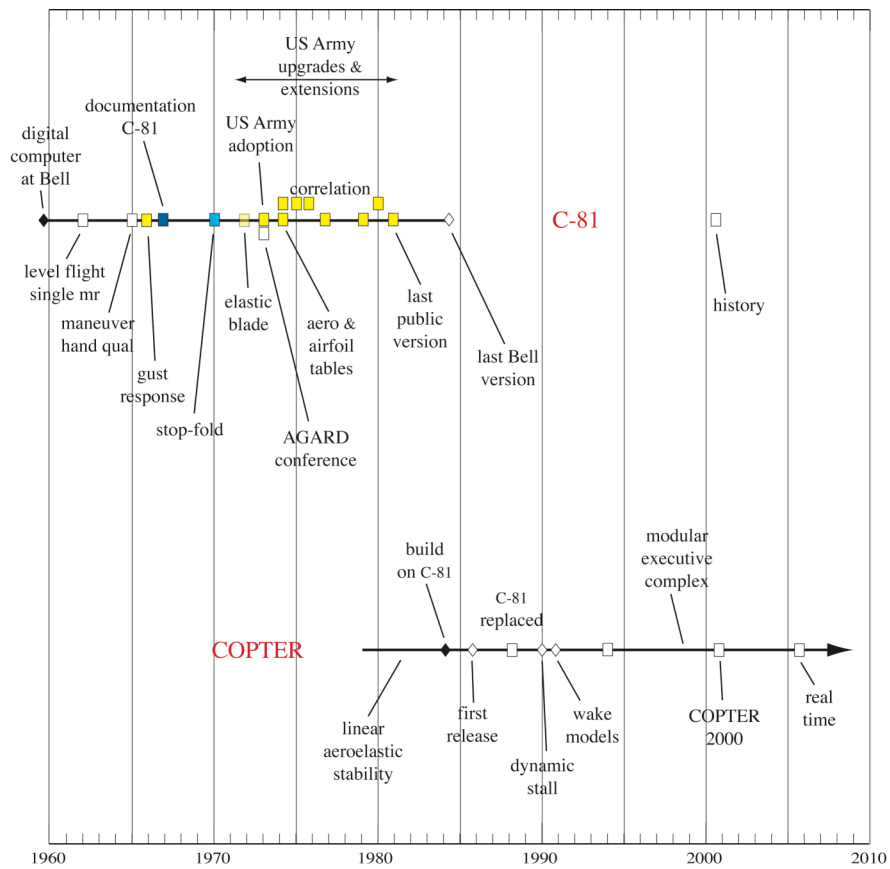


Figure 2. Comprehensive analyses at Bell Helicopter.

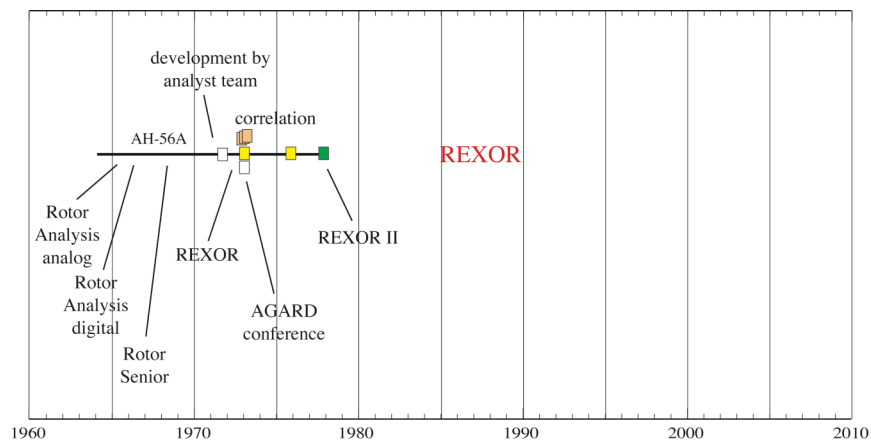


Figure 3. Comprehensive analyses at Lockheed.

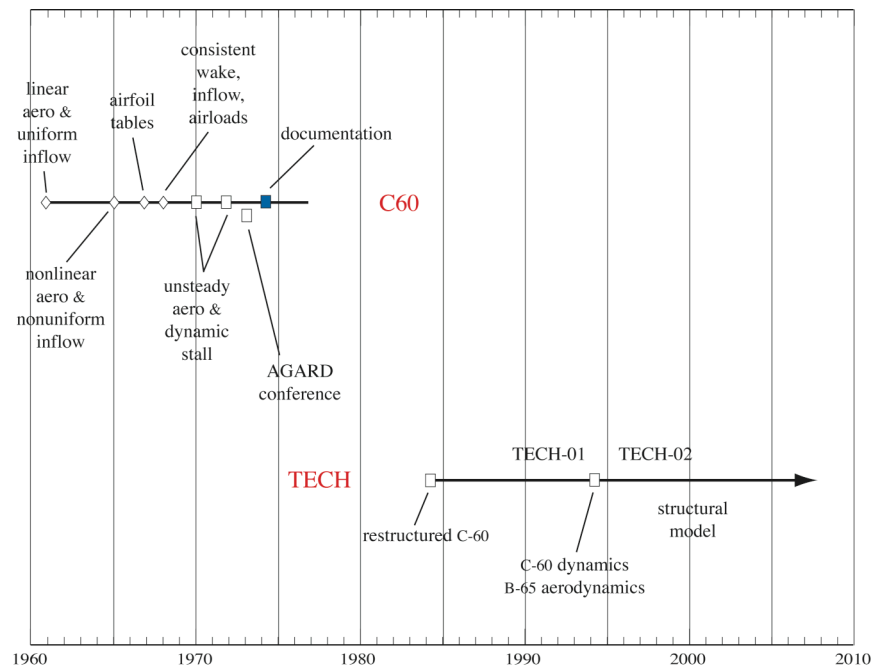


Figure 4. Comprehensive analyses at Boeing.

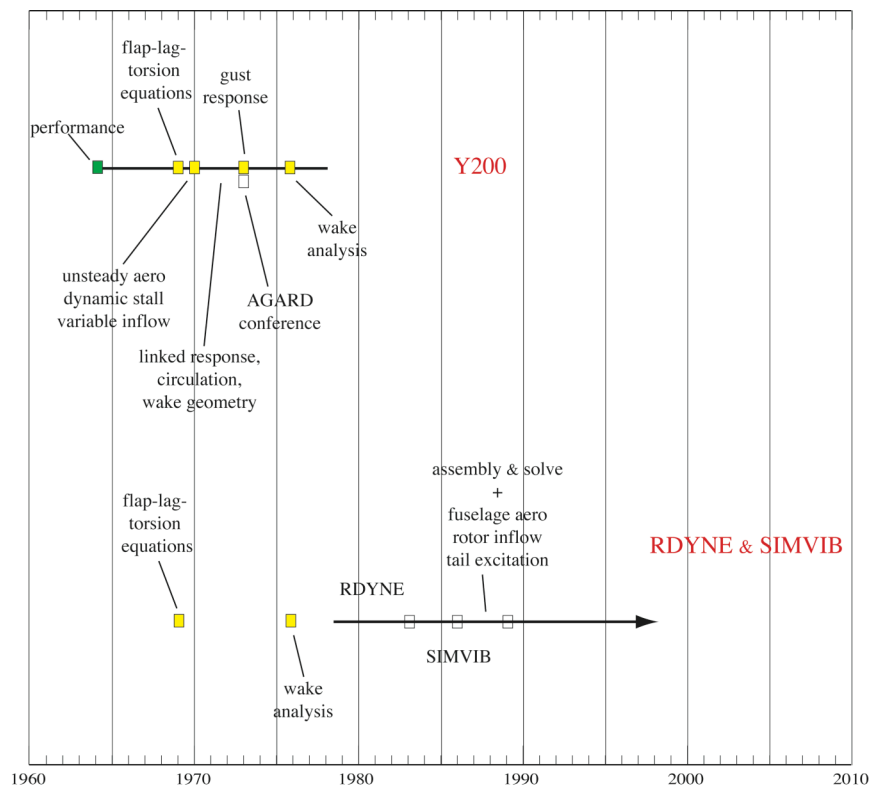


Figure 5. Comprehensive analyses at Sikorsky Aircraft.

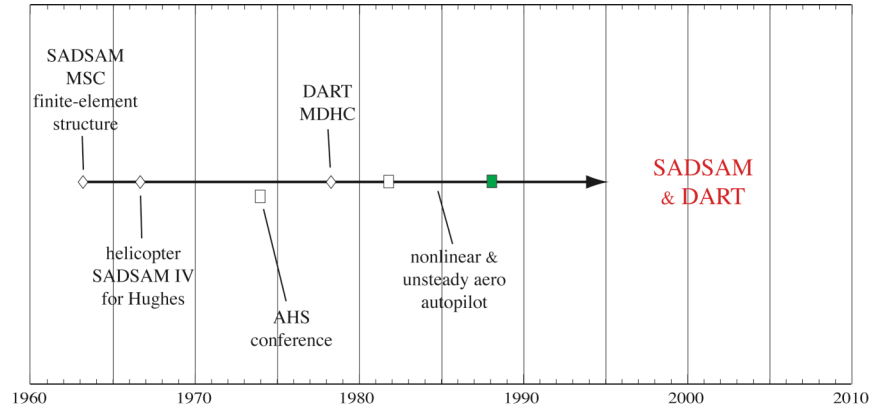


Figure 6. Comprehensive analyses at Hughes and McDonnell Douglas.

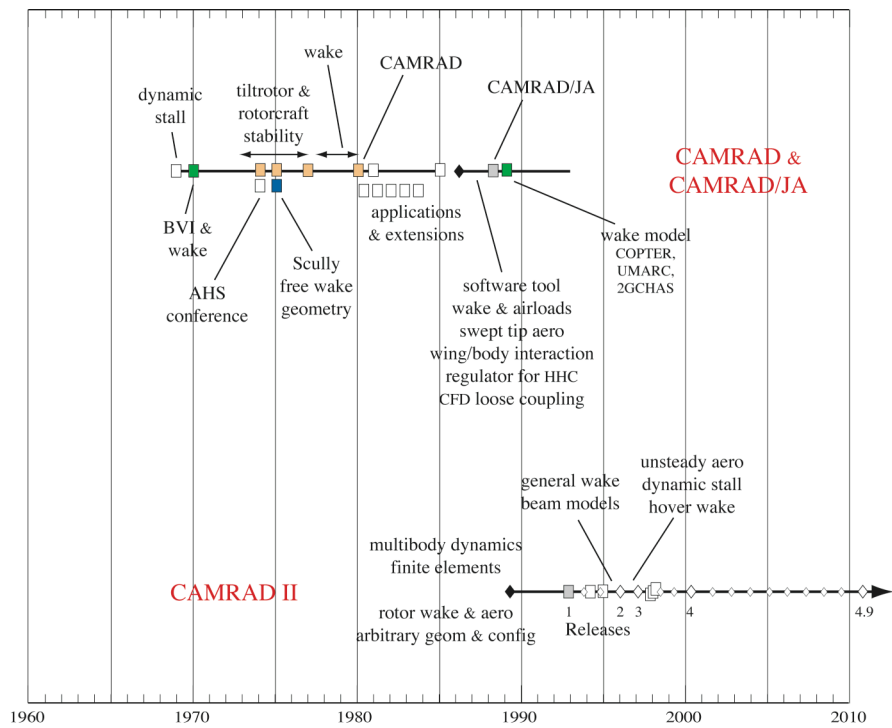


Figure 7. Comprehensive analyses at NASA and Johnson Aeronautics.

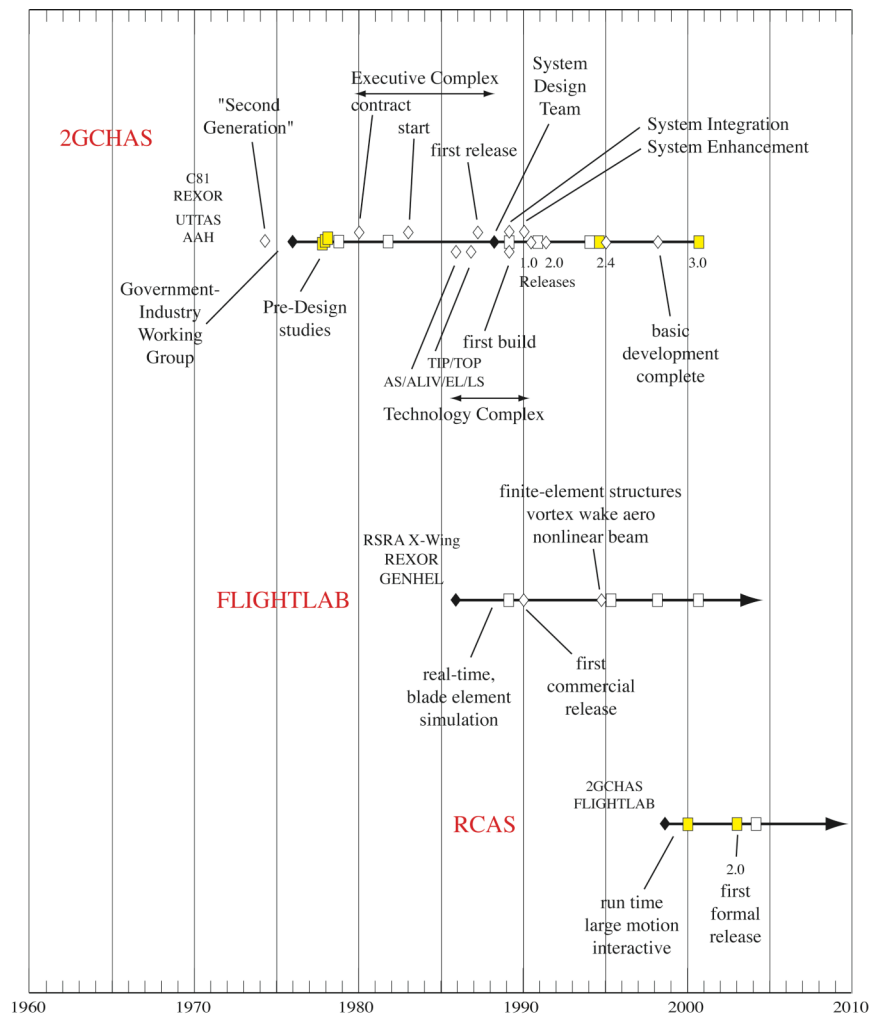


Figure 8. Comprehensive analyses at U.S. Army and Advanced Rotorcraft Technology (ART).

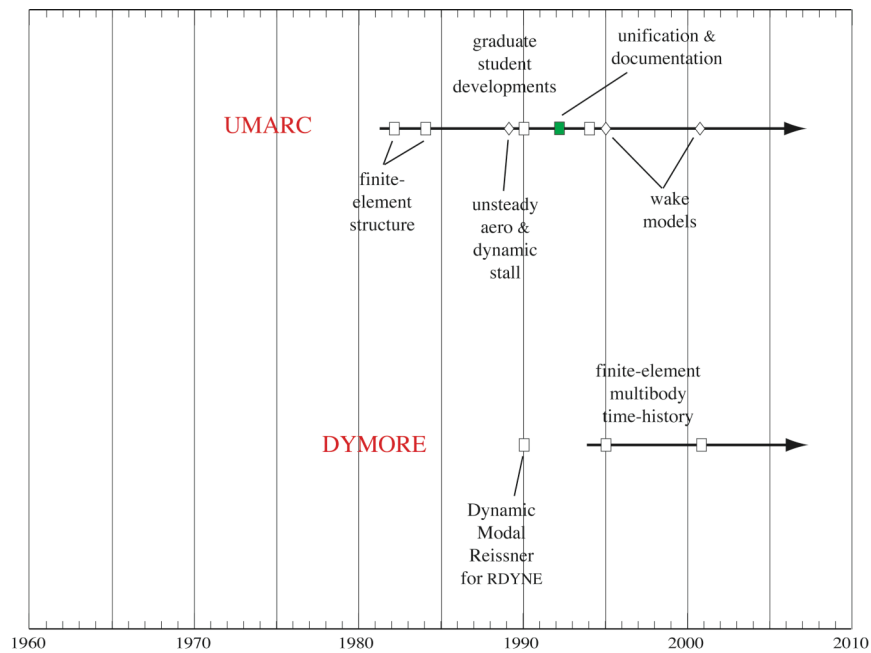


Figure 9. Comprehensive analyses at universities.

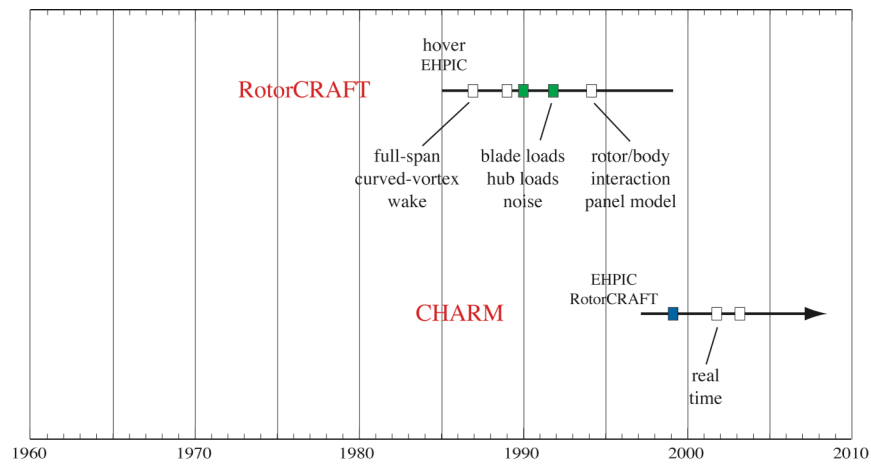


Figure 10. Comprehensive analyses at Continuum Dynamics, Inc. (CDI).

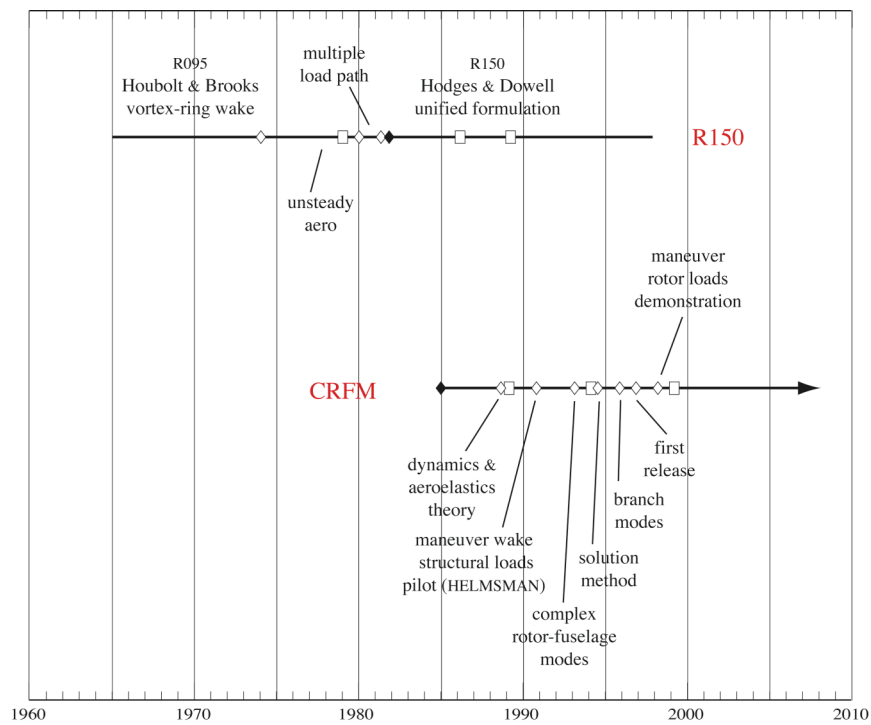


Figure 11. Comprehensive analyses at Westland Helicopters.

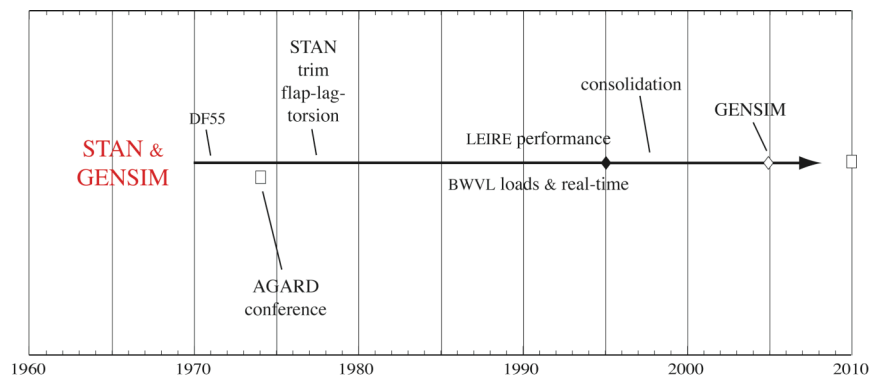


Figure 12. Comprehensive analyses at Messerschmitt-Bölkow-Blohm (MBB) and Eurocopter.

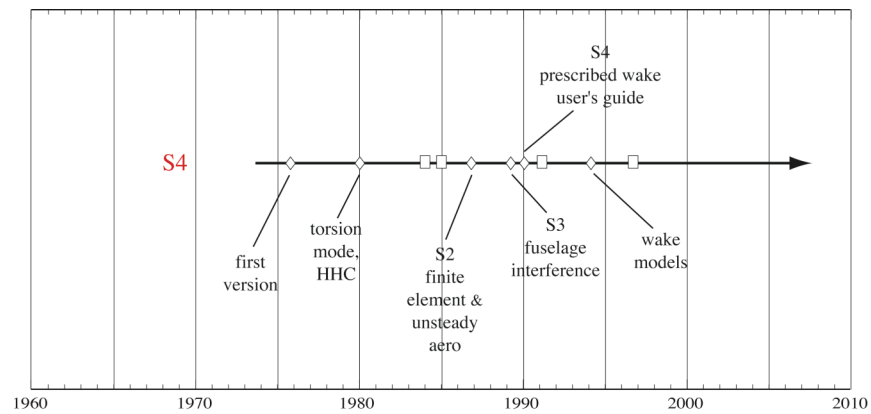


Figure 13. Comprehensive analyses at German Aerospace Center (DLR).

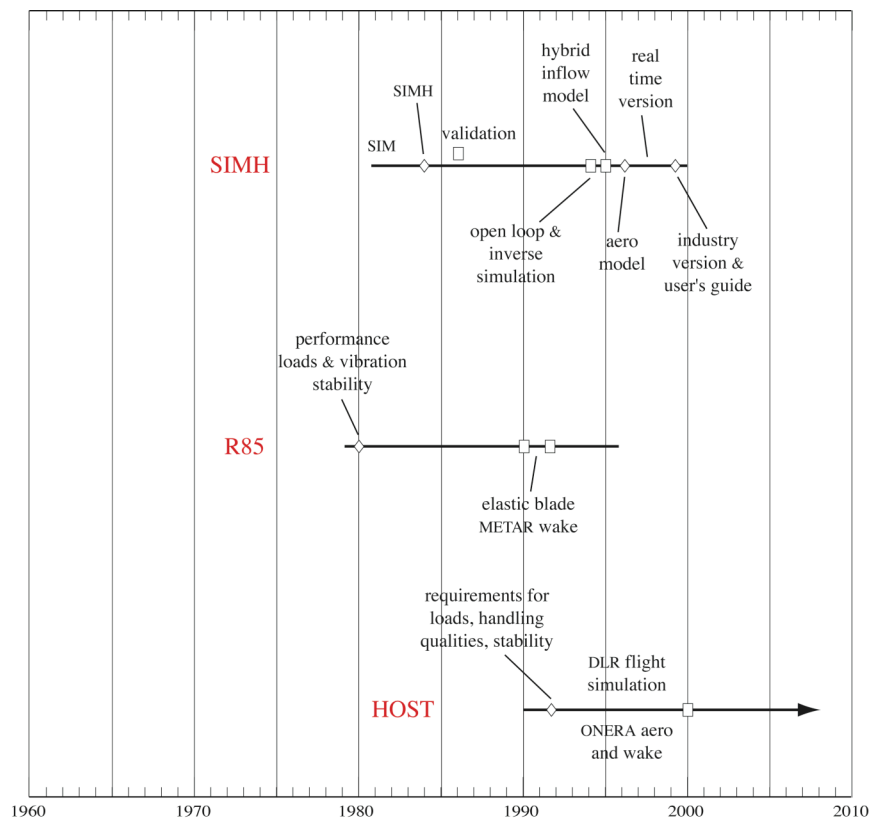


Figure 14. Comprehensive analyses at DLR, ONERA, and Eurocopter.